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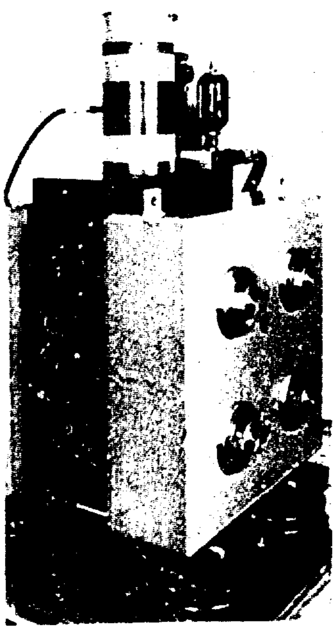

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MISCELLANEOUS PAPER GL-83-19

SEISMIC ANALYSIS OF TUNNEL BORING MACHINE SIGNALS AT KERCKHOFF TUNNEL

by

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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION • U.S.

August 1983

Final Report

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In conjunction with OCE project AT40-CO-007, "Tunnel Detection in Rock," a field evaluation of Mine Safety and Health Administration (MSHA) seismic detection system was performed at a site near Fresno, Calif. The MSHA system was originally designed for deployment after a mine disaster so that trapped miners could be located using seismic signals which they would generate by pounding on the ceiling or floor. The concept of this system was thought to be directly applicable to military needs in locating clandestine (Continued)

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20. ABSTRACT (Continued).

tunneling activity.

The objective of this evaluation was to determine the ability of the MSHA system to detect a large tunnel boring machine (TBM) operating in granite at depths in excess of 1300 ft, the degree of accuracy of the system in locating the TBM, and the maximum range for reliable detection and location.

Early reconnaissance revealed that the natural site noise was approximately 4 ips. Signals received above that level could be processed with a high degree of confidence. During the series of tests, it was determined that the TBM could be detected at a horizontal range of about 8000 ft and the tunnel boring machine could be accurately located within approximately 100 ft at a slant range of approximately 5000 ft. Certain characteristics of an operating TBM were evident within the seismic signature. These were start-up, shutdown, placement of gripper pads, and boring operations.

It was concluded that TBM signal amplitudes were approximately 100 times the amplitude of natural noise on the surface above the operation and would likely be observable to distances of about 10,000 ft or more at sites similar in geology to the Fresno site. In view of the successful evaluation of the MSHA system, recommendations were made for tailoring the equipment and its deployment for special application to military needs.

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PREFACE

The study reported herein was performed by Professor Roy J. Greenfield, Pennsylvania State University acting as a Consultant, during the period August-December 1982, under Purchase Order No. DACA 39-82-M-0142. The overall investigation was sponsored by the Office, Chief of Engineers (OCE), U. S. Army, under Project No. 4A762719AT40, Task CO, Work Unit 007, entitled "Tunnel Detection in Rock." The OCE Technical Monitor was Dr. C. A. Meyer and the U. S. Army Engineer Waterways Experiment Station (WES) Technical Monitor was Mr. R. F. Ballard, Jr.

The field work was planned and carried out under the direction of Mr. J. Kravitz, Mine Emergency Operations, Mine Safety and Health Administration. The field work and logistical operations were done by The Mine Emergency Operations Integrated Logistic Support Group of Westinghouse Electric Corporation. Westinghouse personnel participating were Messrs. J. Moore, Program Manager, R. Rouiller, G. Keeney, W. Dekle, J. Savoy, J. Hartman, and H. Hannah. Computer programming assistance was supplied by Mr. D. R. Greenfield.

Permission to use the Karckhoff Tunnel for these tests was granted by the Pacific Gas and Electric Corporation. Mr. R. Kunz of Auburn Constructors assisted this project in many ways.

The project was conducted under the general supervision of Dr. W. F. Marcuson III, Chief, Geotechnical Laboratory (GL), WES, and Dr. A. G. Franklin, Chief, Earthquake Engineering and Geophysics Division (EEGD), GL, and under the direct supervision of Mr. Ballard, EEGD. Other EEGD personnel actively involved in this project were Mr. J. P. Koester and Dr. G. W. Deer, EEGD, and Mr. C. Cox, Instrumentation Services Division, WES.

COL Tilford C. Creel, CE, was Commander and Director of WES during the preparation of this report. Mr. Fred R. Brown was Technical Director.

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CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimeters
miles	1.609347	kilometers
pounds (force)	4.448222	newtons

SEISMIC ANALYSIS OF TUNNEL BORING MACHINE SIGNALS TAKEN AT KERCKHOFF TUNNEL

PART I: INTRODUCTION

1. The U. S. Army Engineer Waterways Experiment Station (WES) has been actively involved in tunnel detection for over 15 years. Progress in this area was recently reviewed by Ballard (1982); many methods were discussed.

2. There are a number of applications of the ability to detect and locate boring and tunneling operations. Passive detection of seismic signals generated by these operations is a promising method and is the subject of this study. Little information is currently available on the nature and size of the seismic signals generated by these activities. The Kerckhoff Tunnel field test and data analysis described in this report is an initial investigation to gather as much information as possible on the seismic signals from a tunnel boring machine (TBM). The purpose of this study is to assess the capability of a surface seismic system to detect and locate tunneling activity and to present data needed for the design of systems to carry out these functions.

PART II: EXPERIMENTAL CONDITIONS

Site Description

3. The Kerckhoff No. 2 project involves a 4-1/2 mile* long tunnel with a diameter of 24 ft. At the time of the test, 31 July to 6 August 1982, the TBM was almost directly below the center subarray of the seismic main array chosen for assessment, as shown in Figure 1. The depth of the TBM was approximately 1300 ft. The rock is a granite. The site is removed from cultural activity under normal conditions. However, because of a brush fire in the area, there was much vehicle and aircraft activity. The fire also burned telephone lines that were to link the seismic equipment truck on site with the tunnel face (its TBM location) Thus, no communication to the face was possible during the tests. The field site is described more fully in Appendix A.

TBM Description

4. The TBM is a 24-ft-diam rotary machine designed for hard rock tunneling. It uses electric motors with a total of 2200 hp to drive 57 cutting heads, applying a total of 2,200,000-lb thrust to the tunnel face. The TBM is held in place by gripper pads that are hydraulically forced against the sides of the tunnel; the grippers are shown in Figure 2. Appendix A gives further details of the TBM.

Equipment

5. The seismic system to be evaluated in the test was the Mine Safety and Health Administration (MSHA) Post Disaster Seismic Location System. This system is based in Pittsburgh, Pa., and is operated by the Mine Emergency Operations Group of Westinghouse Electric Corporation under contract to MSHA. The seismic location system consists of seismic

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* A table of conversion factors for converting U. S. customary to metric (SI) units is given on page 3.

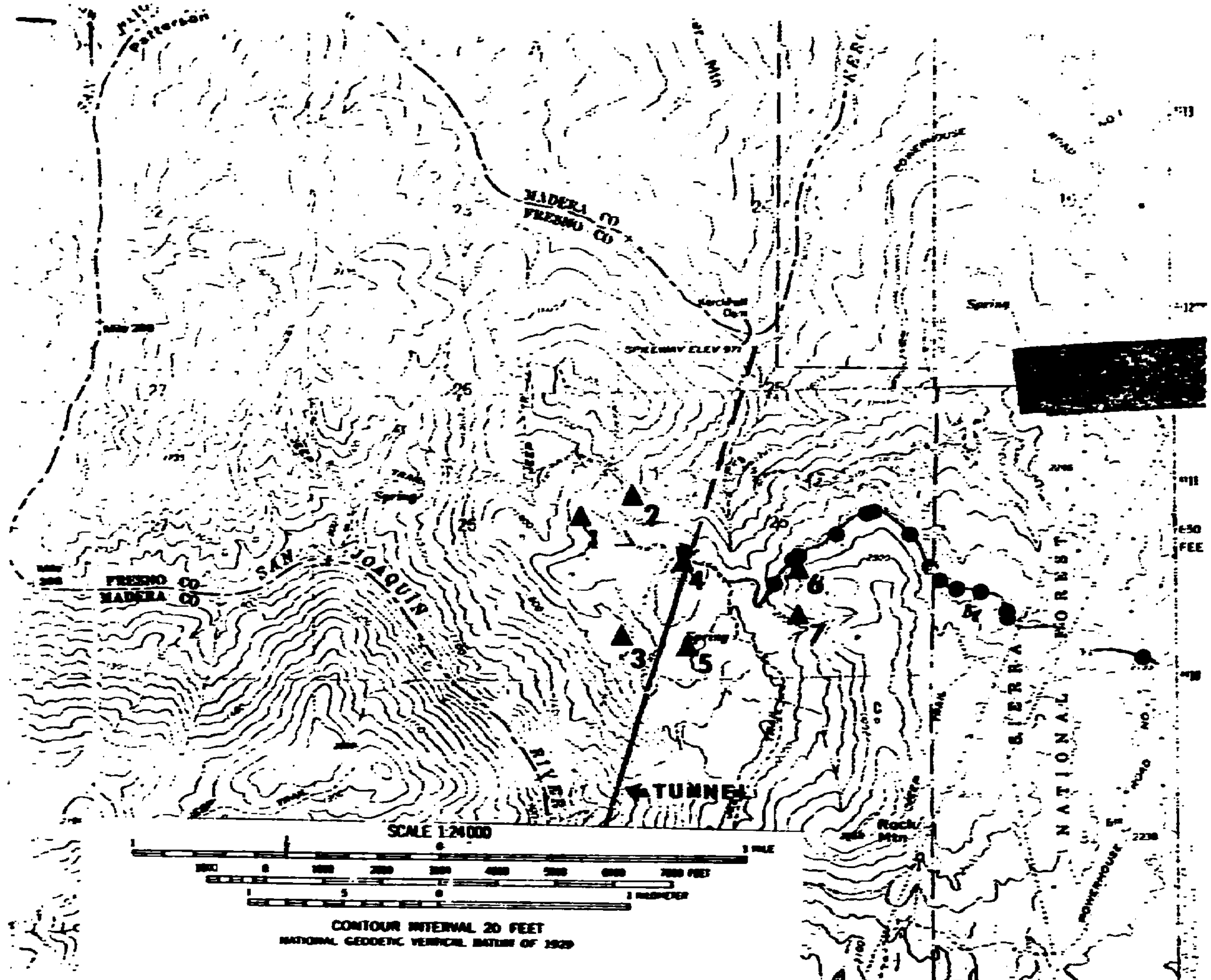

Figure 1. Map of Kerckhoff Tunnel field test site. Triangles show subarray locations. Dots show TBM signal-amplitude measurement points. The TBM was positioned directly below subarray 4 during the test at a depth of about 1300 ft

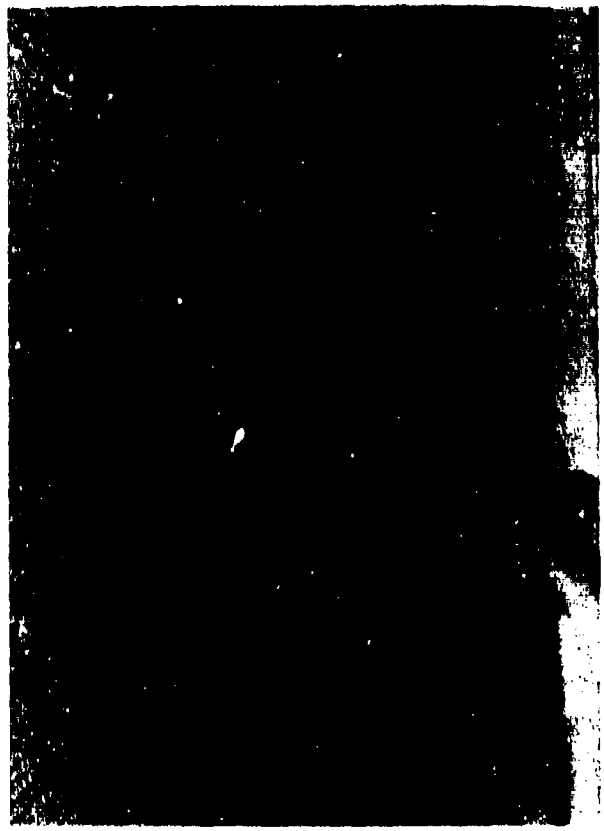

Figure 2. Gripper pad

equipment mounted in a seismic truck, a supply truck, and a separate truck-mounted generator. The primary purpose of this system is to locate miners trapped underground by a mine disaster. The capabilities of the system for safety purposes have recently been described by Durkin and Greenfield (1981).

6. The seismic equipment presently includes seven geophone subarrays, each with a preamplifier and equipment for telemetering the subarray output back to the seismic truck. The MSHA system is in the process of being upgraded to 14 subarrays. In the truck (see Figure 3) are amplifiers, digital notch filters, bandpass filters, a 14-channel high-speed chart recorder, two 14-channel analog tape decks for data

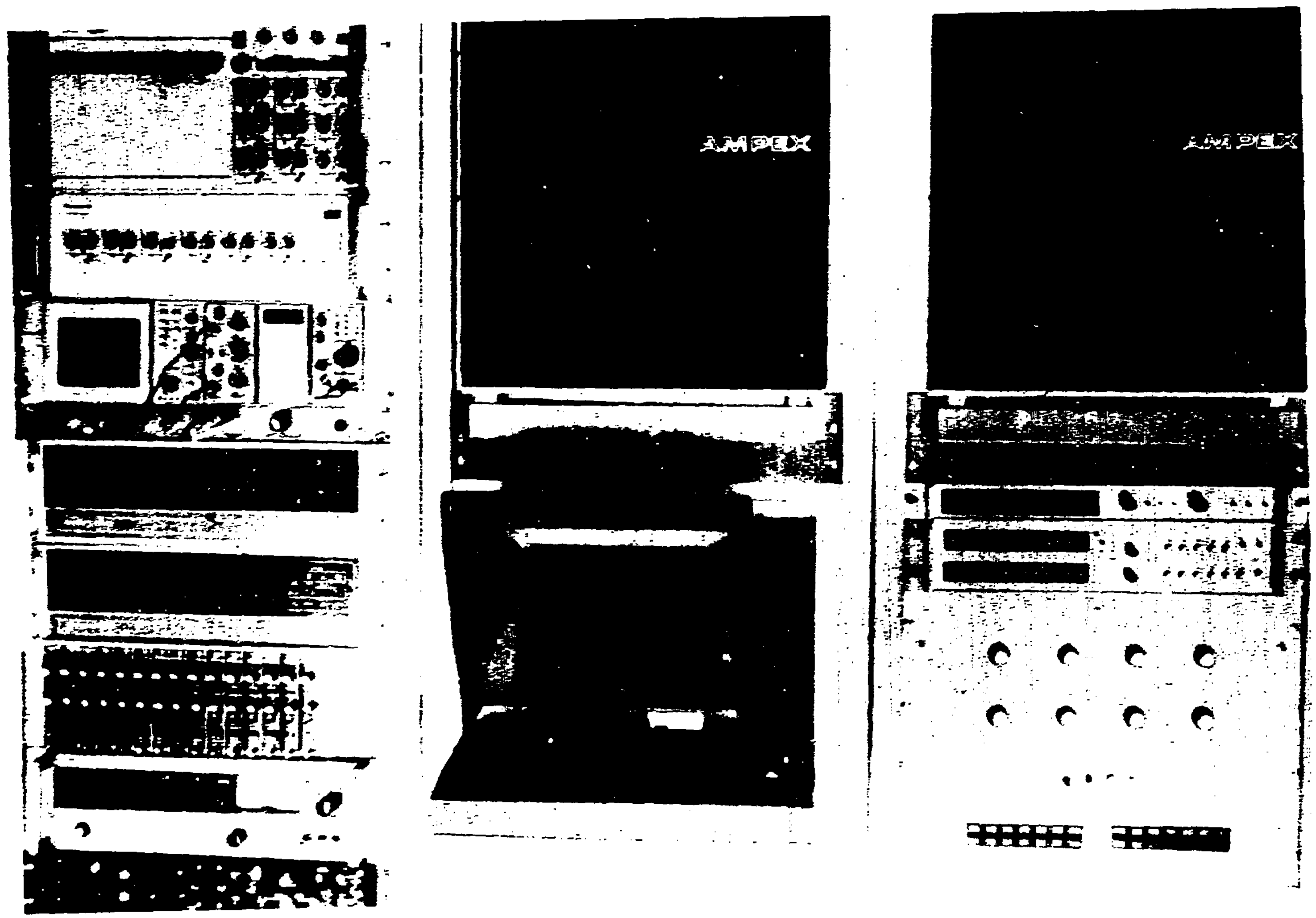

Figure 3. Seismic truck interior

recording, and a Digital Equipment Corporation PDP-11/34 digital computer.

7. The subarrays used in the Kerckhoff Tunnel field test each consist of seven geophones wired together in parallel. Six of the geophones are placed on a 10-ft-diam circle, and the seventh is placed at the center. The geophones are 14-Hz resonance Geospace GSC-11 vertical geophones set to operate at 70 percent of critical damping. The geophones are buried to a depth of a few inches below the ground surface.

8. The digital computer is used for a variety of tasks. It contains an interactive program called TPICK which displays filtered data, allows the analyst to align repetitive signals, adds these signals in phase (stack), then presents the stacked traces to the analyst for arrival time selection. TPICK also computes amplitude spectra of 300-msec data samples. During the processing, seismic traces are displayed to the analyst on a Tektronics 4010 graphics terminal. The computer also has programs to do event location by either the MINER method (Westinghouse Electric Corporation, 1971) or the Least Squares Method (Ruths, 1977). The computer is also programmed to do simple analysis of seismic refraction data.

9. In addition to the seismic truck system, there is a Dresser SIE 12-channel seismic refraction set. The refraction equipment is used to get the P-wave velocity and can be used to measure signal amplitude. This refraction equipment was calibrated, for the Kerckhoff Tunnel field test, against the truck-mounted system.

10. The equipment functioned well in the Kerckhoff test, with one exception. The preamplifiers have an automatic gain control (AGC) which reduces the gain if the signal is approximately 150 μips for a period of time (Dekle,* personal communication; Greenfield, 1982). This AGC is not normally activated in regular MSHA system tests for signals from men pounding on the walls in mines. However, the signals from the TBM were so large that for subarrays within 2000 ft of the point above the TBM the AGC limited the amplitude of the recorded signal. Thus, the absolute amplitudes could not be used for subarrays in this range.

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*W. Dekle, Westinghouse Electric Corporation.

However, absolute amplitudes in the range were measured with the calibrated refraction set.

Chronology

11. The seismic testing was originally scheduled to run from 2-6 August 1982. But a major brush fire interfered with the seismic tests. The fire forced evacuation of the seismic equipment just as seismic measurements were to begin on 2 August. Thus, seismic measurements could not be started until late 3 August. Events selected for discussion will be referred to as identified by the time code generator which is incorporated in the MSHA system, i.e., 217:08:51:32 means calendar day (5 August), hour (0800), minutes (51), and seconds (32).

PART III: SITE NOISE

Noise Levels

12. During much of the recording time, the area of the seismic array had higher than normal noise levels because of the man-made noise associated with the fire fighting effort. To get an estimate of natural noise levels at this site, data were selected that represented low noise levels during periods when no obvious man-made noise was present. Table 1 gives examples of the noise amplitudes at these times. The lowest noise levels in the table are on the order of 4 µips. This level was seen on a number of other observations during the course of the field test. Durkin and Greenfield (1981) gave a range of 1 to 10 µips for noise in the 20 to 200 Hz band. It is probable that over a long period of time quiet low wind conditions would occur giving a noise level somewhat lower than 4 µips, perhaps as low as 1 µips at the Kerckhoff site.

Table 1

Noise Levels (Peak-to-Peak µips)

Date	Time	Description	Measured With	Amplitude µips
4 Aug	10:21	Vehicle	S2	150.0
4 Aug	10:09	LN	S5, S6, S7	4.0
5 Aug	9:04	LN	S3, S5, S7	7.0
6 Aug	12:16	LN	S5, S6, S7	3 to 4
6 Aug	14:03	LN	Refraction gear	4

NOTE: LN = Low natural noise
S2 = Measured with subarray 2, etc.

Spectral Character of the Noise

13. Amplitude spectra were calculated for a period of low noise. The calculation was done on the DEC 11/34 computer on the truck. A

periodogram (Fourier transform) was taken of 300 msec of noise and the magnitude of the Fourier amplitude spectra plotted (see Figure 4). No spectral smoothing or averaging was done. The noise spectra shown are fairly flat over the whole frequency band. Other noise samples not shown were examined in the time domain and appear to have spectra that are not flat. However, the portions of the spectrum that contained most energy varied; it was different at a given time on different subarrays. It was observed by Durkin and Greenfield (1981) that natural noise often falls off slightly with frequency over the 20 to 200 Hz band.

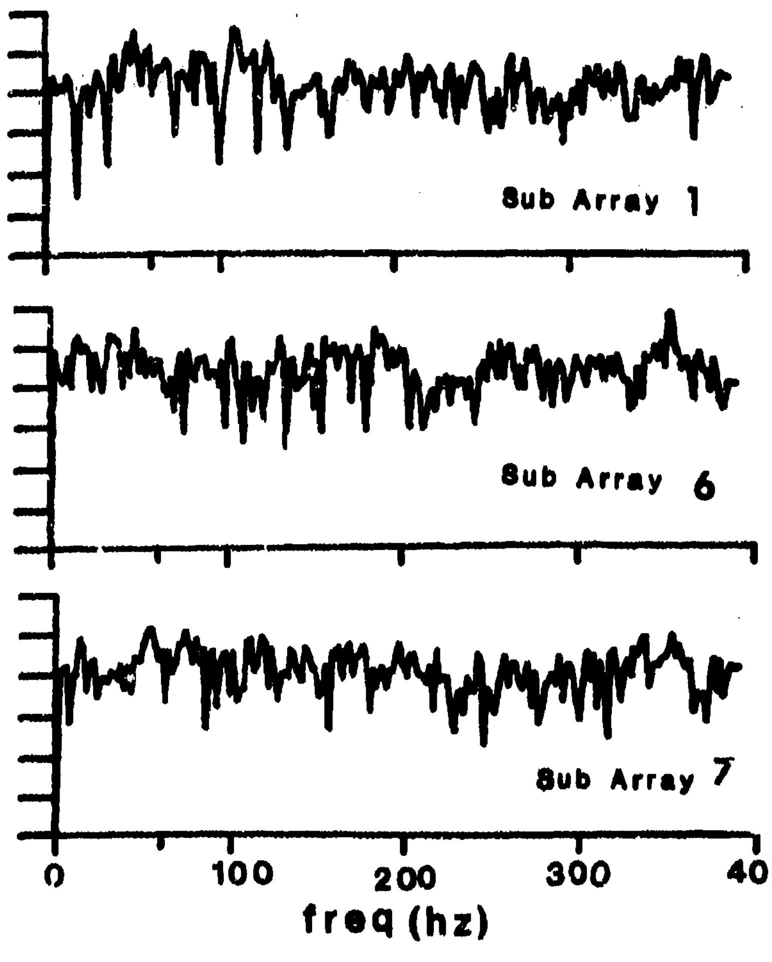


Figure 4. Noise spectra. Ticks on vertical axis are 10 db

PART IV: SIGNALS

Signal Amplitude Versus Horizontal Range

14. A profile of maximum particle velocity data was taken to determine how the TBM (as shown) signal amplitude varied with horizontal distance (r) from source. For logistical reasons the profile was taken along the jeep trail shown in Figure 1. However, an added advantage of taking data on the trail was that the elevation changes were limited to less than 100 ft at any point on the profile.

15. The data used for the measurements of amplitude were taken with two recording systems: a single vertical geophone connected to the calibrated seismic refraction system and a single vertical geophone telemetered back to and recorded at the seismic truck. The data taken with the truck system were not used when there was a possibility of clipping. Amplitudes are given in μips of ground velocity. Several seconds of data were examined and the largest peak-to-peak amplitude used. Figure 5 gives a plot of amplitude versus distance. A fit was made to

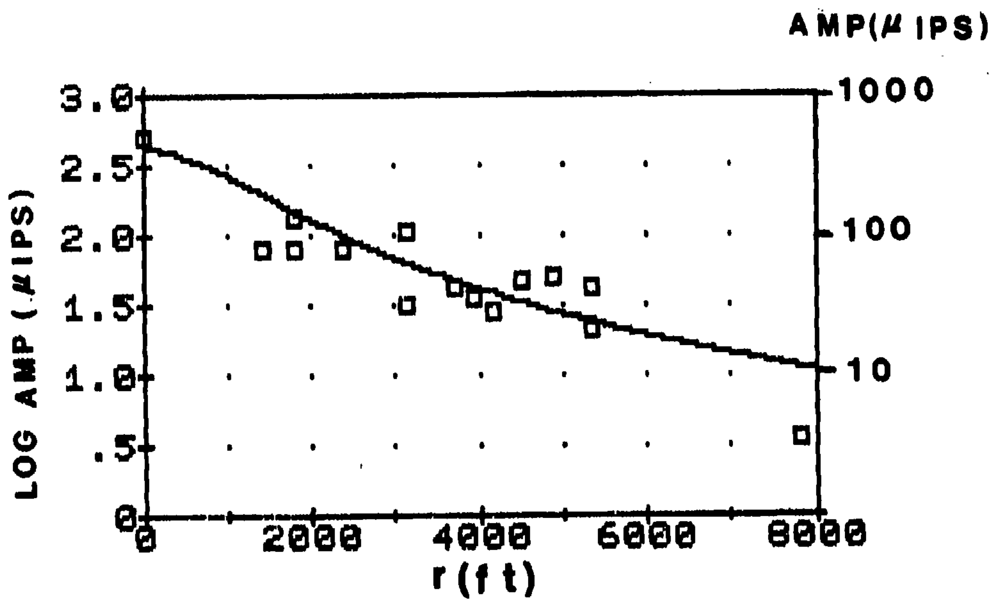


Figure 5. Plot of TBM signal amplitude versus range

the amplitude data of the form

$$A(r) = \frac{C_a \cos \theta}{R} = \frac{C_a h}{R^2} \qquad (1)$$

where

$A(r)$ = peak-to-peak amplitude as a function of horizontal range r (μips)

θ = angle to the vertical

C_a = a constant

R = slant range from TBM to geophone (Figure 6) (ft)

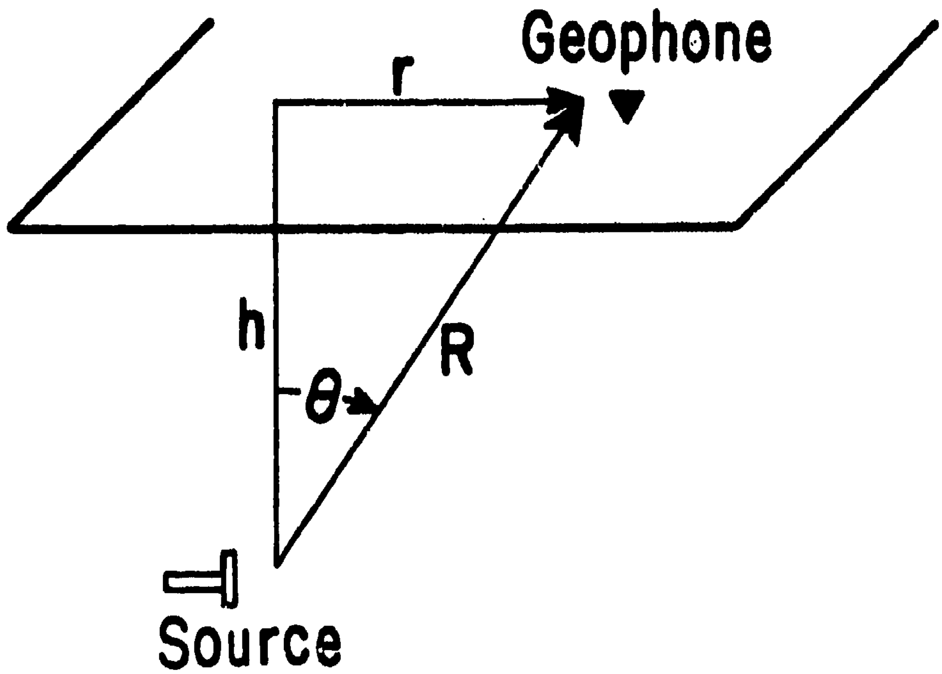


Figure 6. Geometry for signal model

16. The form given in equation 1 was used for two reasons. First, it is a reasonable form for the vertical ground velocity if it is assumed that the TBM acts as an isotropic P-wave source. The amplitude in the far field goes down as $1/R$ because of geometric spreading, with the particle motion being nearly in the radial direction. To get the vertical component, it is necessary to multiply the radial amplitude by

cos Θ . The second reason for using this form is that it gave the best fit, according to the study of Durkin and Greenfield (1981) of amplitude variation for underground blows.

17. The value of C_o was found by calculating the average

$$C_o = \frac{1}{N} \sum_{J=1}^{N} A_J \Big/ \left[\frac{\cos \Theta_J}{R_J}\right] \qquad (2)$$

where

A_J = amplitude (μips)
R_J = slant range (ft)
Θ_J = angle for the j^{th} measurement

The method of calculating C_o given in equation 2 follows from a least-square criteria. The 15 data points, shown in Figure 5, were used in the fit giving a value of $C_o = 5.3 \times 10^5$ (μips · ft). The resulting curve is also plotted in Figure 5.

18. The value plotted at 7800 ft was used in the fit, but may have been noise and not a TBM-induced signal. The inclusion of this point did not have a major effect on the curve that was obtained.

Spectral Character of the TBM Signal

19. The Fourier amplitude spectra of the TBM signals are shown in Figure 7. These spectra are for signals taken during a long period of TBM operation. The spectra differ in detail between subarrays, but the overall pattern is similar on each. The spectra are highest between 20 and 70 Hz and decrease gradually with frequency above this range.

20. There is no indication of particular spectral peaks that are common to all subarrays. This lack of spectral common peaks probably reflects the nature of the TBM source as a large series of random impulses. The overall shape of the spectra reflects the effects of propagation, receiver site response, and attention during propagation.

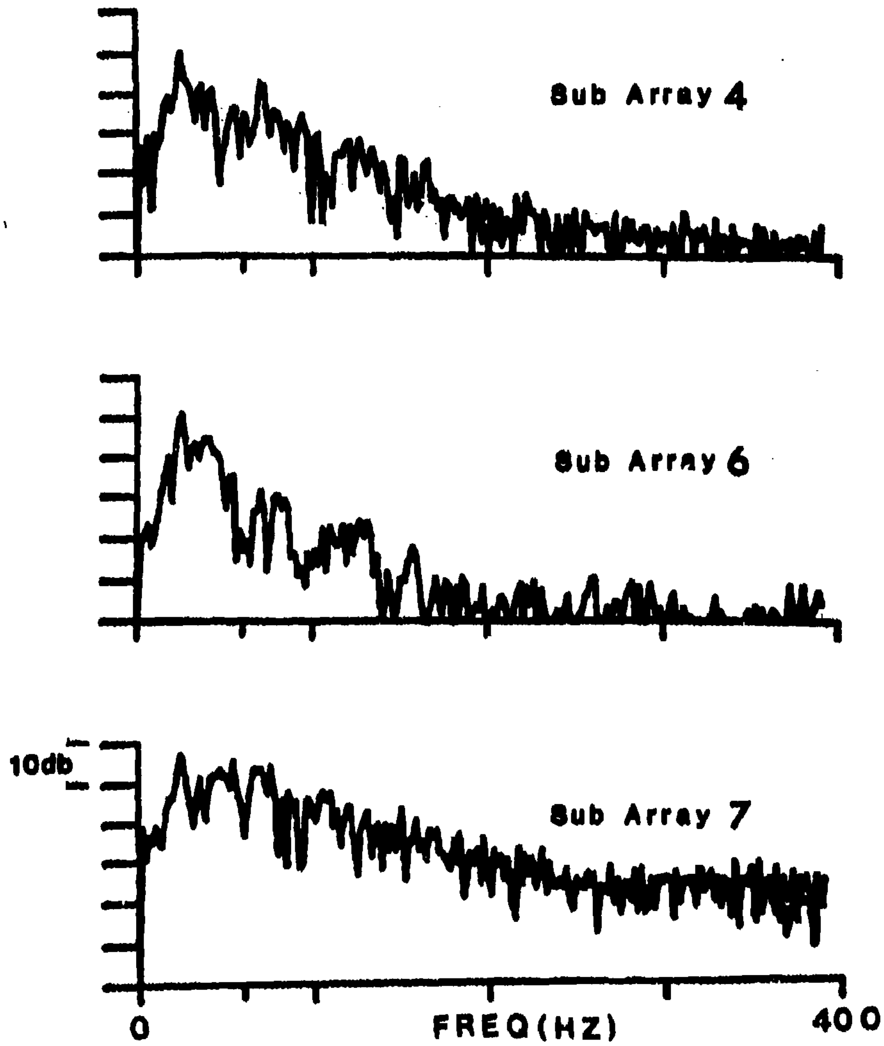


Figure 7. TBM signal spectra. Numbers give channel.
Vertical ticks are 10 db

In particular a low-velocity layer of unconsolidated soil could be expected to cause spectral peaks. There was not a great deal of soil overburden in the test area; thus spectral resonance due to reverberations in the soil were not expected and do not appear to have been encountered.

Signal From a Man Hitting the Tunnel Wall

21. Signals were generated by Westinghouse personnel in the tunnel on the morning of 4 August. The majority of the signals could not be seen on the seismic system set up because of the high noise levels (up to several hundred μips) from vehicles and aircraft involved in fire fighting. Because of lack of communication between the tunnel and the seismic truck, it was not possible to have the signaling done during the occasional quiet periods.

22. A few signals were, however, received on the surface. Figure 8 shows part of a series of signals from blows made with a 40-lb timber hitting the floor of the tunnel. The largest peak-to-peak amplitude was 10 μips. This amplitude is approximately 2-1/2 times the noise levels at the quiet times during the Kerckhoff test. This suggests that it would be possible to detect the hammering involved in tunneling activity.

23. Durkin and Greenfield (1981) did an extensive study of seismic signals from underground blows. The amplitude predicted by that study for a 1300-ft-deep source is 27 μips. The data for use in that study were, in the main, taken in lower compression (P-) wave velocity rock at coal mines. A wave form modeling procedure, in Durkin and Greenfield, showed that the signal amplitude should be proportional to the square of 1/(rock P-wave velocity). Thus, the high velocity of the rock at Kerckhoff probably explains why the signal amplitudes, for the Kerckhoff test, were below the average found by Durkin and Greenfield.

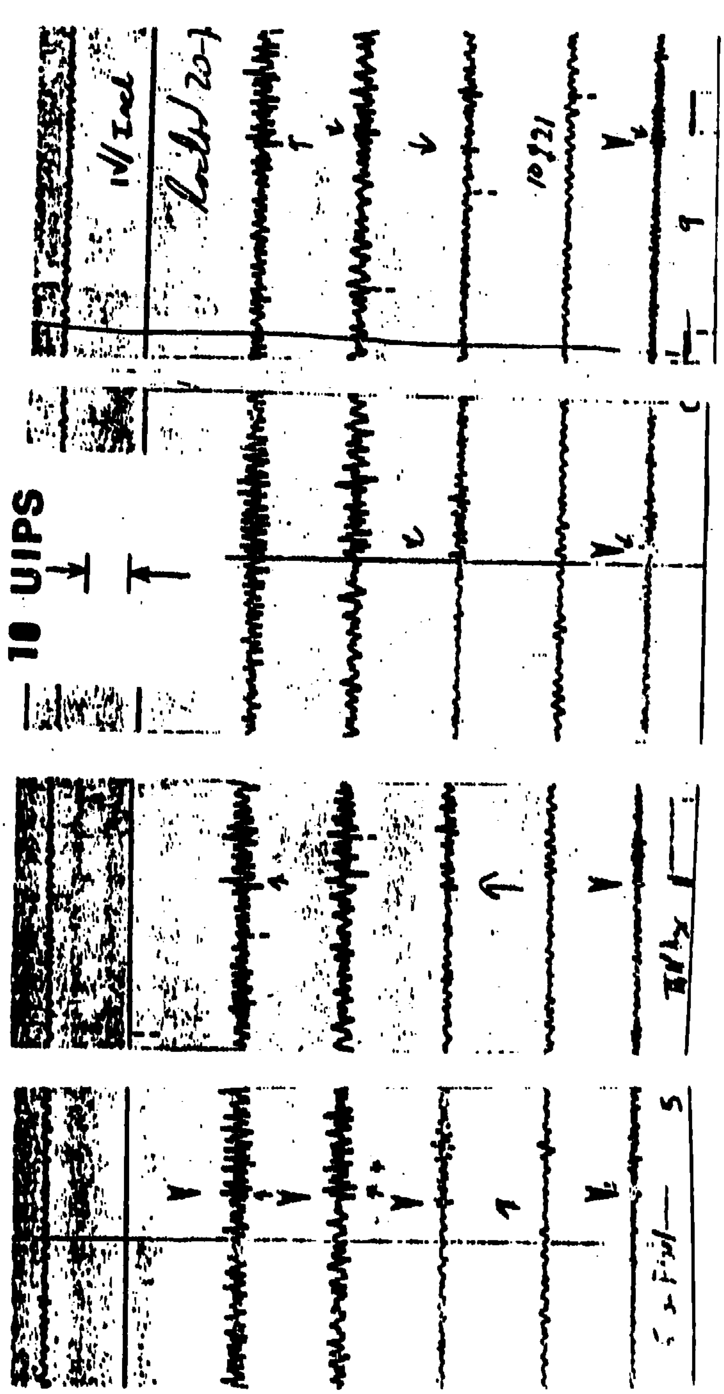


Figure 8. Blows from man in tunnel

PART V: DETECTION RANGE

24. The data described in Part IV demonstrated directly that signals could be seen to horizontal source-to-receiver distances, r , of 5000 ft. Based on the noise measurement and the signal model given in equation 1, it is possible to estimate at how large a range r it would be possible to detect the Kerckhoff TBM. Since, at many times, the noise level will be 4 μips or below, it is reasonable to require a signal amplitude of 8 μips or greater (6 db above noise) for detection. On this basis, detection should be possible to r of 8000 ft during periods of low surface noise.

PART VI: METHODS FOR MASKING THE TBM SIGNAL

25. The organization doing the tunneling might attempt to avoid detection of their TBM activity. To mask the seismic signals from the TBM, it is necessary to limit tunneling operation to periods when some other source is generating seismic noise with an amplitude at the subarrays that is higher than the TBM signal. Several mechanisms which could create noise will be considered.

Explosions

26. During the field test refraction surveys were used to determine velocity structure. The source was a stick of dynamite. The record of one of these explosions, recorded on the subarrays is shown Figure 9. The source-to-subarray distances vary from 80 to 1600 ft. The maximum amplitudes on these records are 520 μips. This amplitude may have been limited by the AGC of the preamplifiers. It should be noticed that the signal only lasts at high amplitudes for approximately 0.5 sec. Thus, it would be necessary to set off explosions at a rate of more than 1 per sec to mask a TBM. This does not seem to be a practical method of masking.

27. A number of investigations of the seismic signals from surface explorations have been carried out over the years by the U. S. Bureau of Mines. Wave forms shown by Stagg and Engler (1980) indicate that the signals last on the order of a few seconds at most, in agreement with the Kerckhoff observations. Signal duration will generally increase with distance, while amplitude decreases. There is a large variation in peak-signal amplitude with geology. However, several studies (e.g. Stagg and Engler, 1980; Devine et al., 1966; or Siskind et al., 1980) allow an approximate estimate of the peak explosive signal amplitude as a function of distance. Based on Figure 10 of Siskind et al. (1980) for a 1-lb charge, peak ground velocities are approximately 50,000 μips at 100 ft; 5,000 μips at 1,000 ft; and 500 μips at 100 ft. They give an amplitude dependence proportional to the square root of the charge weight. The amplitudes based on the Siskind et al. curve were approximately a factor of 10 higher than those shown in Figure 9 for Kerckhoff refraction explosion.

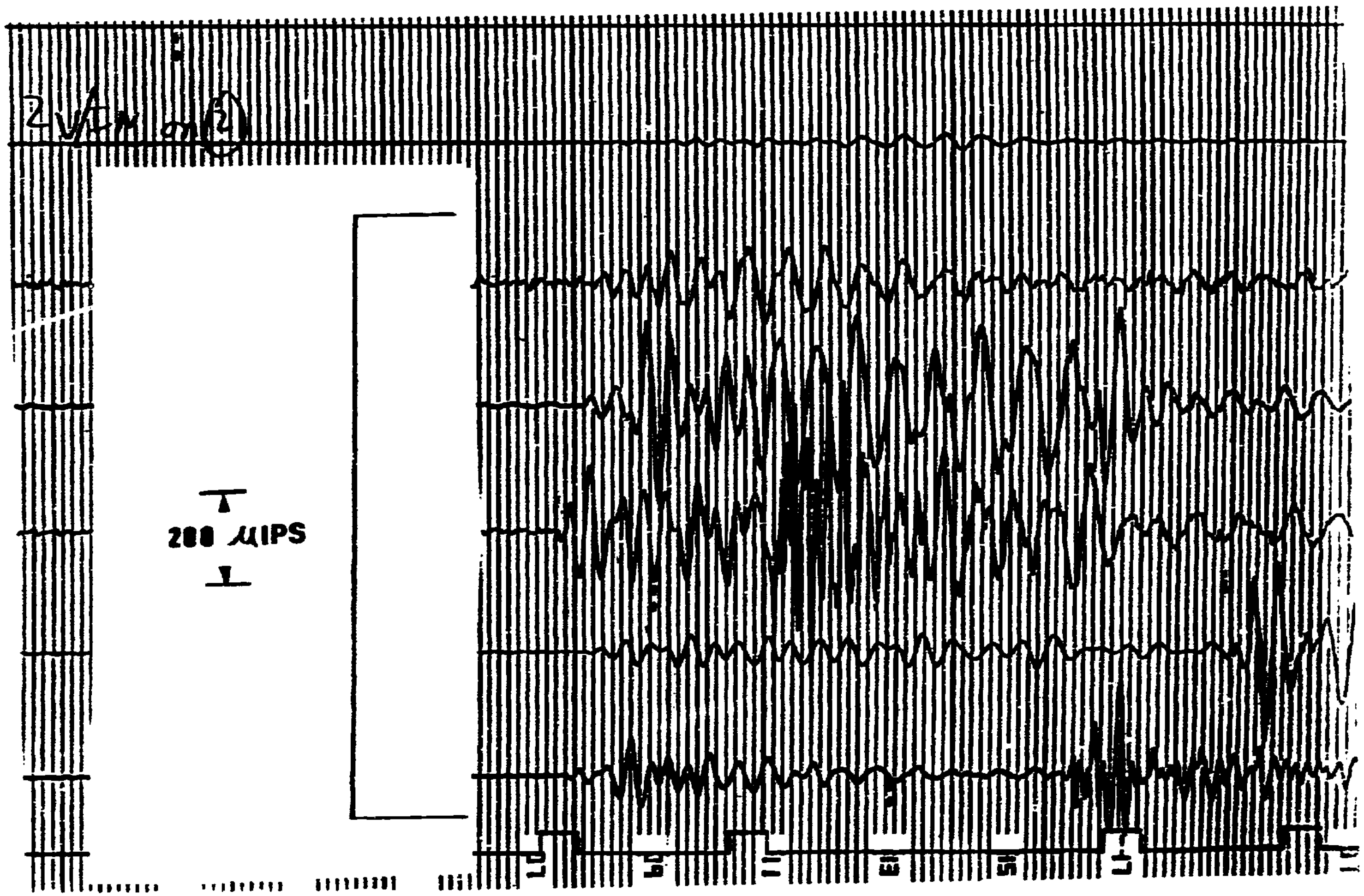


Figure 9. Record of refraction explosion taken with subarrays

Some of this difference is probably due to the hard rock and very shallow soil at Kerckhoff, and the AGC may have limited the Kerckhoff amplitudes.

Fixed Machinery

28. A large machine at the surface could generate seismic noise of a level comparable to the TBM. Subarrays should not be located near machines. If a machine is at a fixed position, it is possible to use subarray processing methods to greatly reduce the noise from the direction of the machine.

Natural Noise

29. High wind or rain will raise noise levels. The effect of wind can often be reduced by planting subarrays in flat areas without trees or high grass. Compared to single sensors, the use of subarrays usually reduces natural noise levels (Durkin and Greenfield,1979). It is probable that burying the geophone will also be very effective in reducing noise, though the method needs further study.

30. Since it is a source of noise, subarrays should not be located near running water.

Aircraft

31. Helicopters and low-flying airplanes generate high levels of seismic noise through the coupling of sound to earth. These aircraft can generate noise levels above the TBM signal level. The noise field may be significant at several miles from the aircraft. Thus, during periods when aircraft are in the air, the noise could mask the TBM activity.

Motor Vehicles

32. Automobiles and trucks can generate high levels of seismic noise. The amplitudes are highly dependent on the site geology and the way the vehicle is driven. However, the amplitude of this noise rapidly decreases with distance, and typically traffic more than one-quater mile away will not generate significant noise. Thus, a particular vehicle will not interfere with more than one subarray if spacings are 2500 ft or greater.

PART VII: IDENTIFICATION CRITERIA FOR A TBM

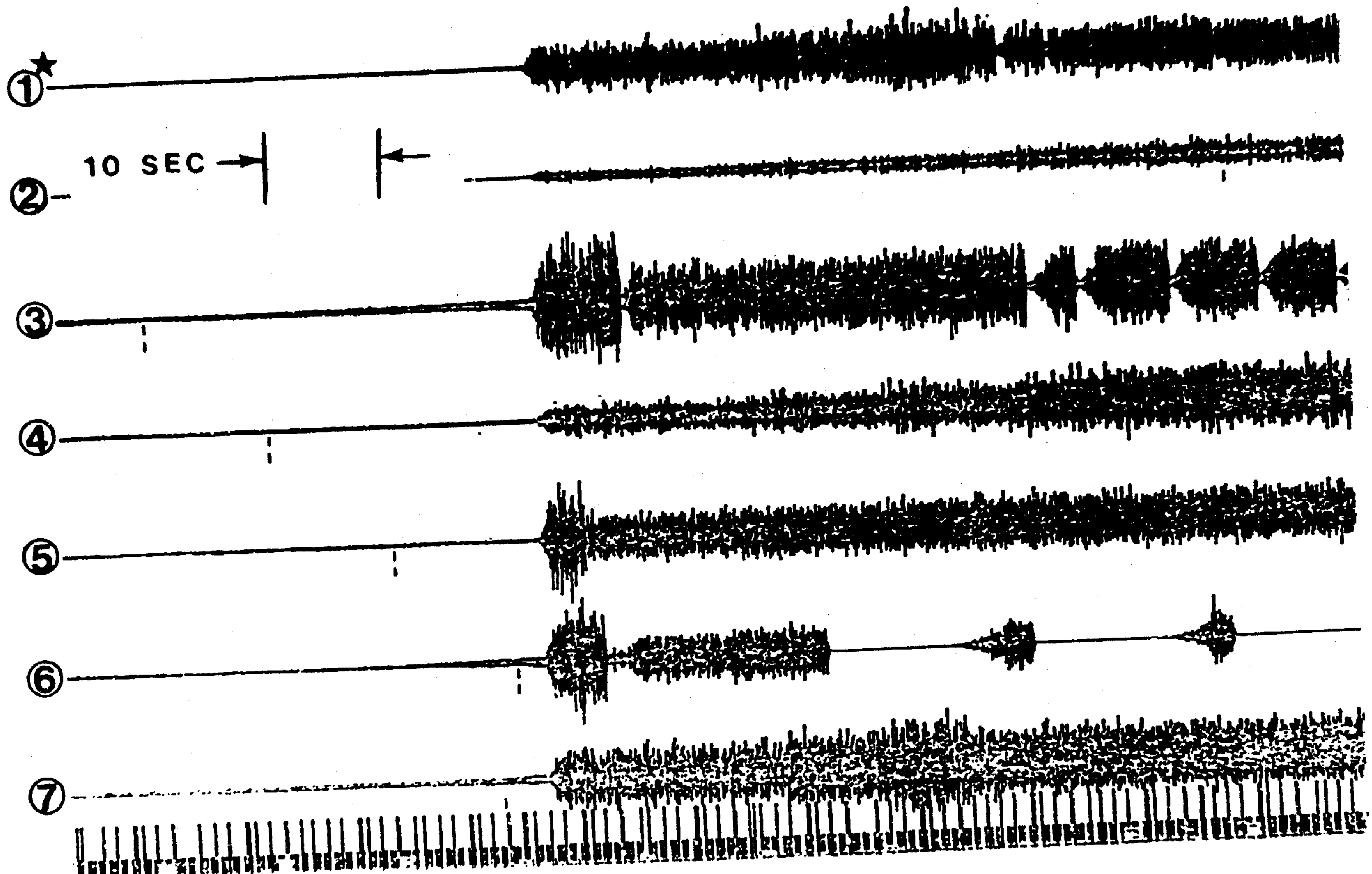
33. An effort was made to find characteristics of the signals from the Kerckhoff TBM which would be useful in identifying a signal as originating from a TBM.

34. The first characteristic of the TBM signal which is useful for identification is the character of the signal at start-up and shutdown. It is physically impossible for a TBM to operate continuously because of maintenance and repositioning activities. The signal from the TBM starts from background noise and reaches its full amplitude over a period of 3 to 15 sec. The time taken for the signal increase is similar on all the subarrays which were spread over a 1900-ft-diam array. In a search for an unknown TBM, this similarity would indicate that the signal on all subarrays probably has a common source.

35. Examples of start-up and shutdown records are shown in Figures 10-16. The increase in amplitude during start-up probably represents the period of time when pressure of the rotating cutting head against the face is at its full value.

36. The cessation of cutting (shutdown) occurs when the cutting head is backed off from the face. The signals decrease to background noise level in a similar manner at all subarrays when this backoff occurs. The time for this decrease to occur varied from 15 to 25 sec for the backoffs observed.

37. Before the actual application of pressure at start-up and in periods after the shutdown, signals lasting a few seconds or less were observed. A variety of causes is possible for these signals; these include starting and stopping of the TBM motors, motion of the TBM body or cutting head, the increase in pressure as the gripper pads are set, or the dropping of the 300-lb cutter bits. Because of the brush fire at the test site, direct communications between the tunnel face and the seismic truck were not possible, so, generally, it was not feasible to identify the seismic signals with specific source events. However, this is compensated for by the fact that concurrent fire fighting activites lend a significant degree of realism in that they produced



★ Refer to Figure 1 for subarray-1 locations

Figure 10. Start-up of TBM (example 1)

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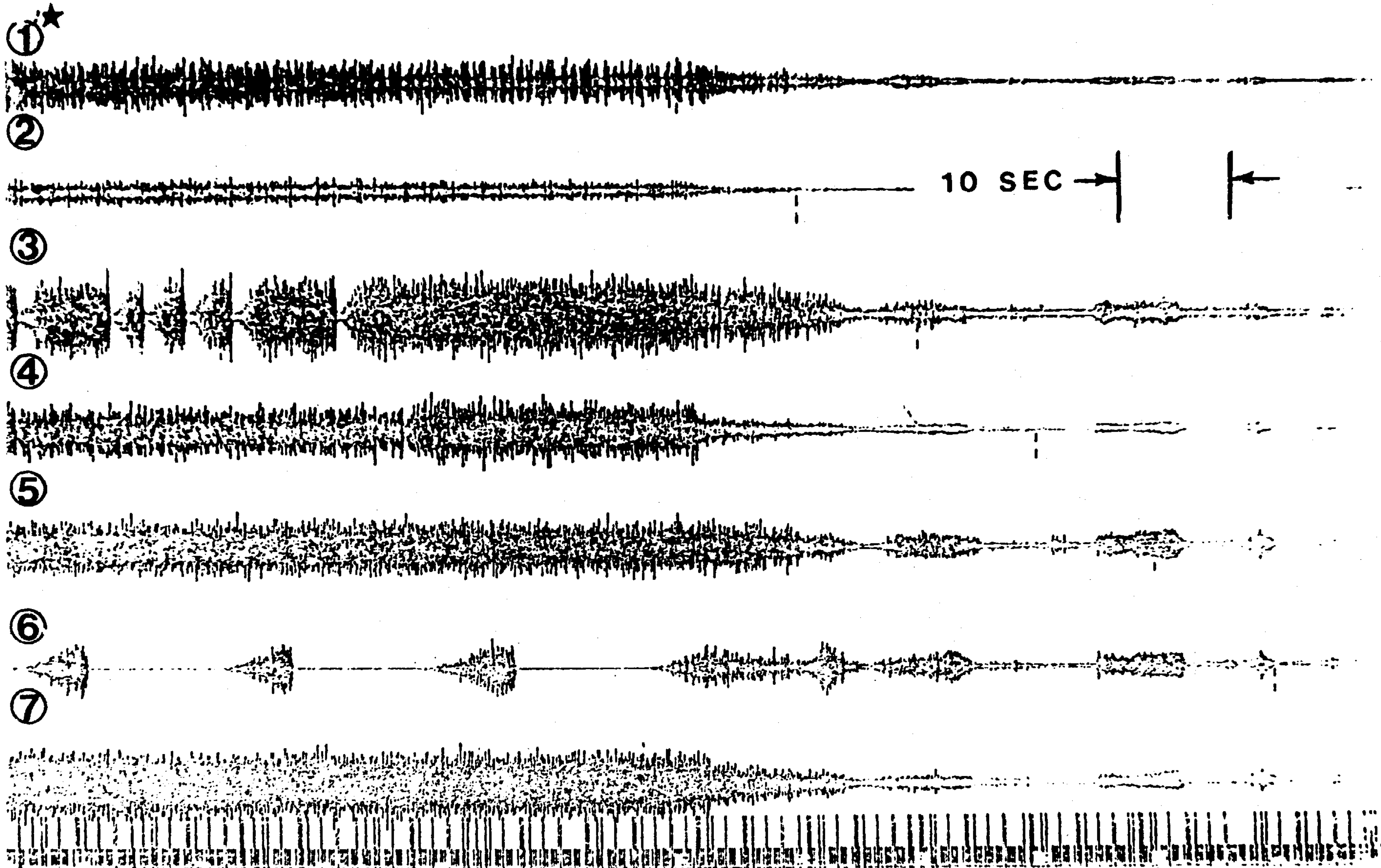

★Refer to Figure 1 for subarray locations

Figure 11. Shutdown of TBM (example 1)

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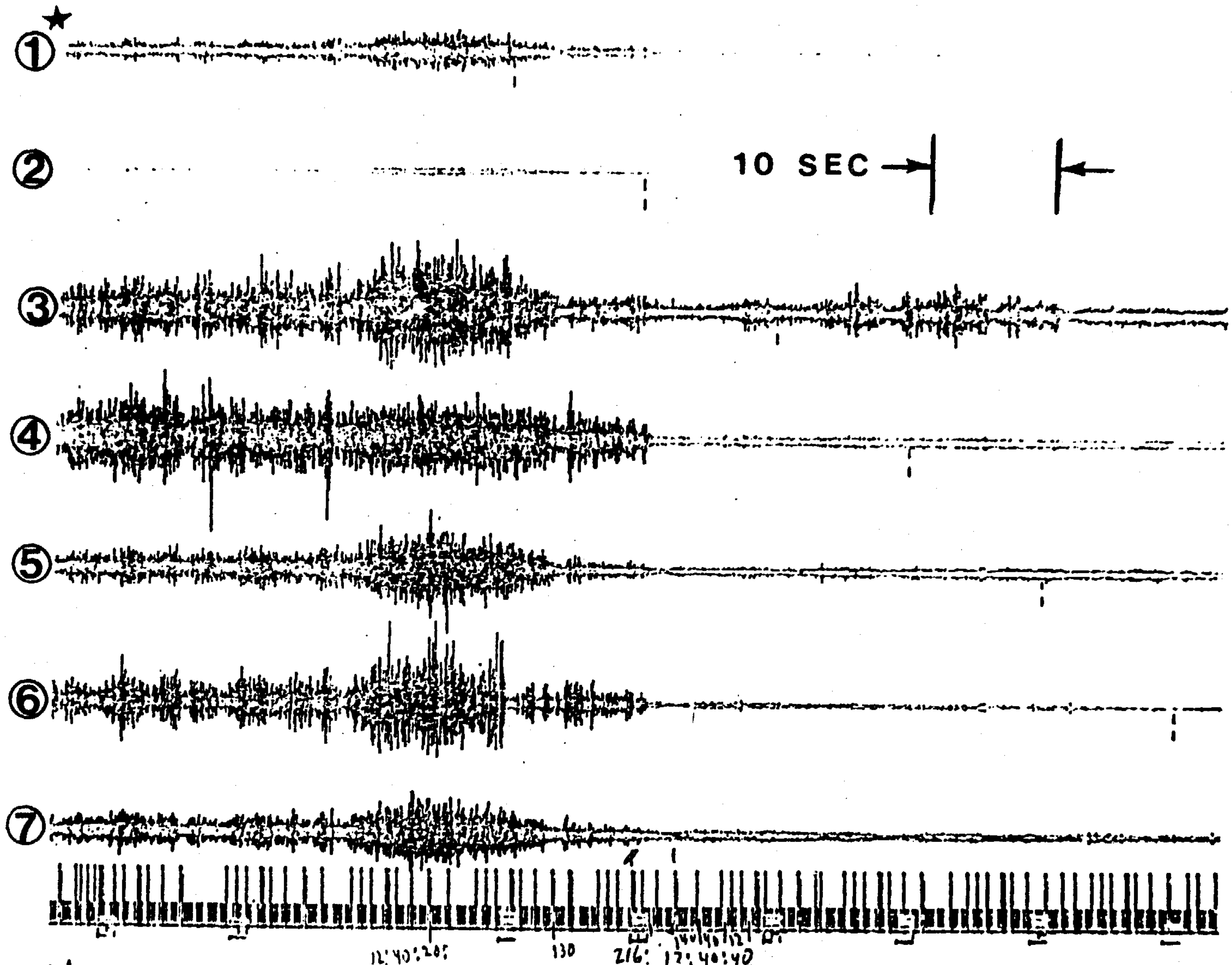

★Refer to Figure 1 for subarray locations

Figure 12. Shutdown of TBM
(example 2)

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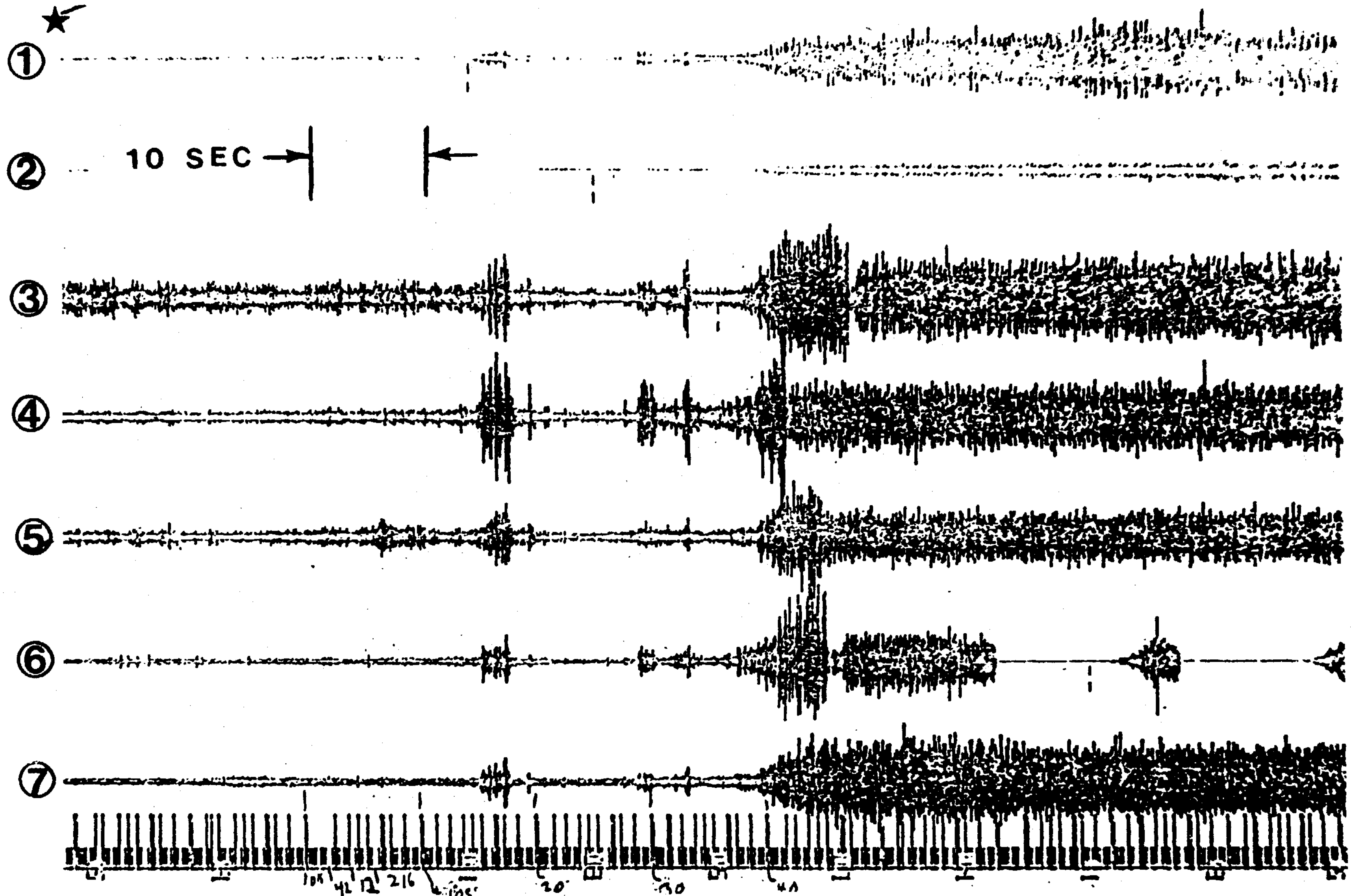

★Refer to Figure 1 for subarray locations

Figure 13. Start-up of TBM
(example 2)

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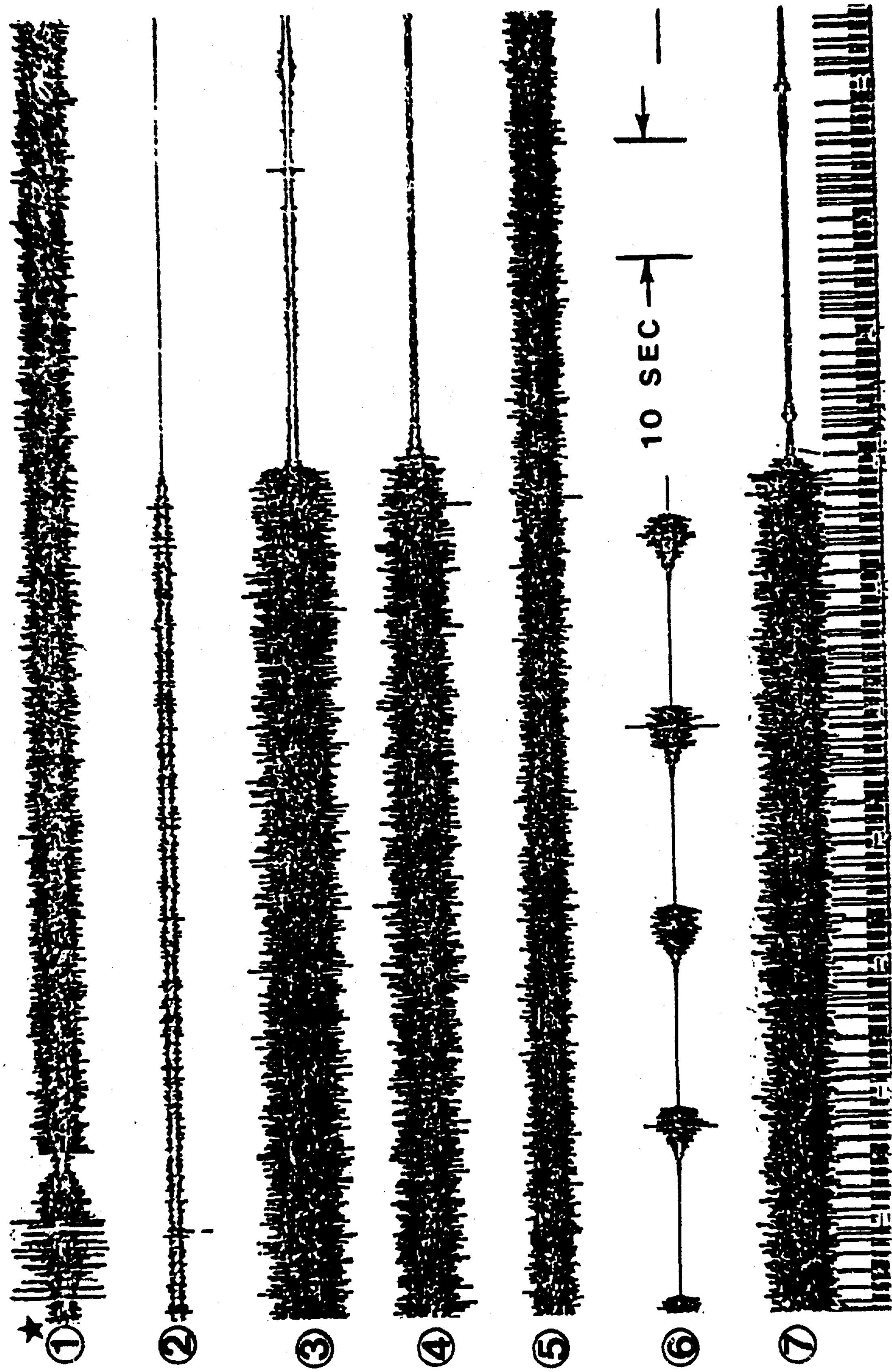

* Refer to Figure 1 for subarray locations

Figure 14. Shutdown of TBM (example 3)

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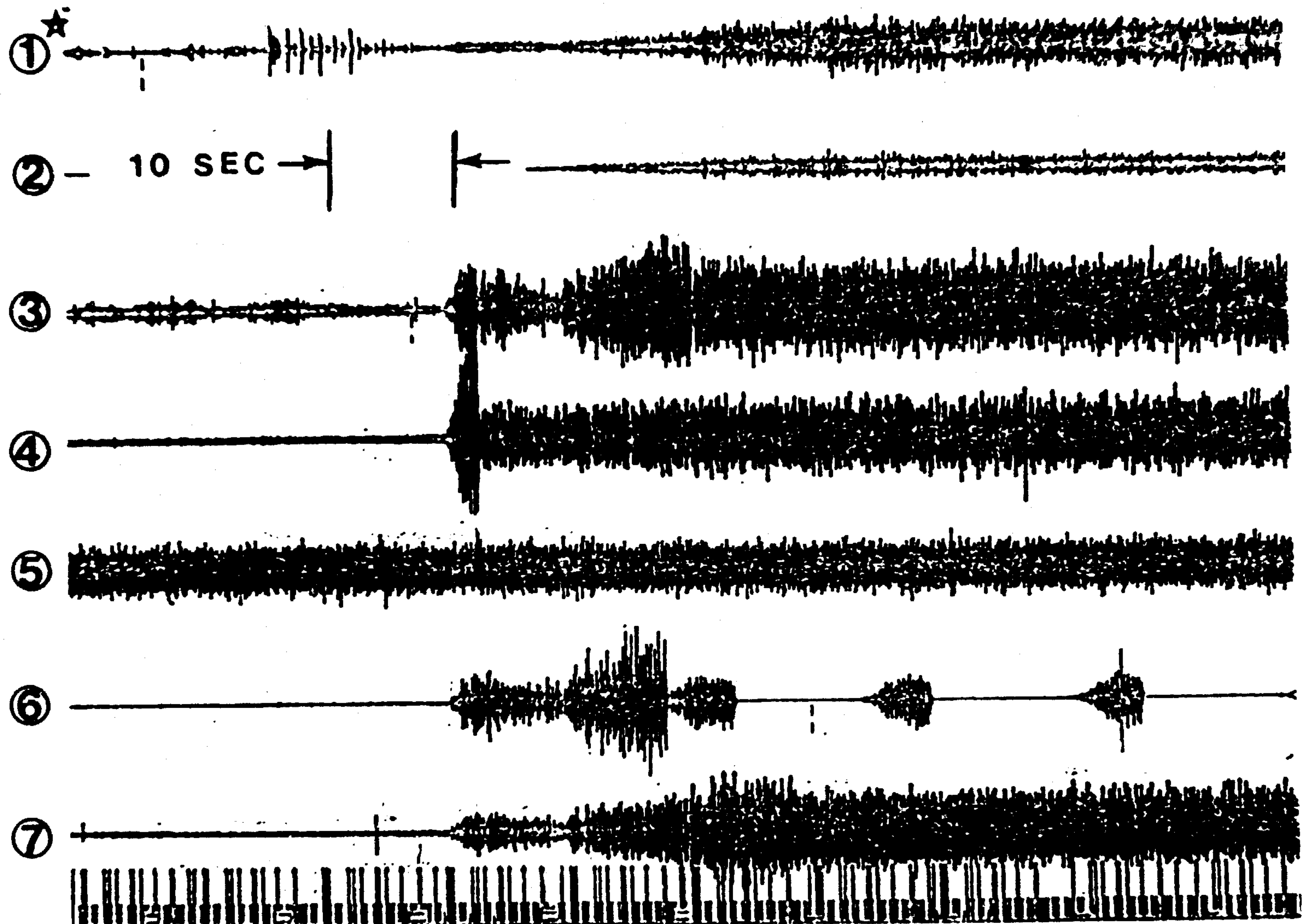

★Refer to Fig. 1 for subarray locations

Figure 15. Start-up of TBM
(example 3)

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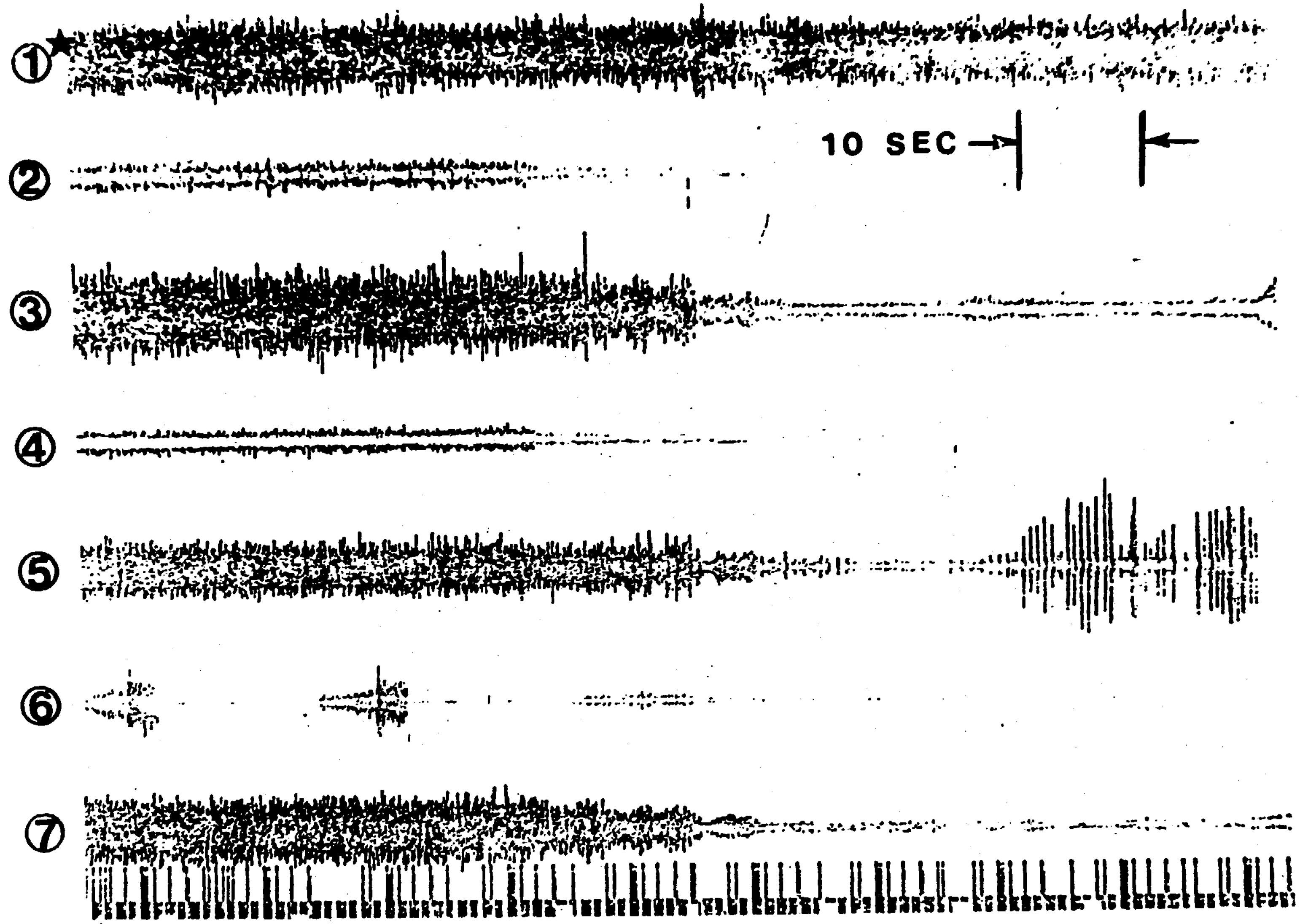

★ Refer to Fig. 1 for subarray locations

Figure 16. Shutdown of TBM
(example 4)

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surface activity levels comparable to those that would be present in real-world situations.

38. It was possible to definitely identify the signals caused by the setting of the gripper pads. Mr. Joseph P. Koester, WES, made observations after a shutdown at 217:08:51. Based on the time sequence of events he observed, it was possible to identify the signals from the setting of the gripper pads; the grippers were set into a position they had already occupied (old position) and also set at a fresh position. These signals are shown in Figures 17 and 18. The signals last for 2 sec for the old position and approximately 10 sec for the fresh position. The first 2 sec of the wave form for the fresh position are similar to the wave form for the old position. The largest peak-to-peak amplitudes are on subarray 3 and are approximately 40 μips for the old position and 100 μips for the fresh position. Mr. Koester noted that the audible noise in the tunnel was much higher at the fresh position than at the old. This was due to the cracking of rock as the points on the gripper pads made holes for themselves. Figure 19 shows an 8 μips playout which illustrates a detail of part of the signal caused by setting the grippers at the fresh position. The signals are emergent, so first breaks cannot be picked for location purposes. The signals have energy between approximately 20 and 100 Hz. For location purposes, it is possible that array processing such as cross-correlation techniques could be used on these signals.

39. An estimate can be made of the distance at which the gripper pad signals can be seen when the grippers are set at a fresh position. If the peak amplitude obeys the same form as equation 1, the amplitude will vary as

$$A(r) = \frac{B \cos \Theta}{R} \tag{3}$$

where $B = 1.92 \times 10^5$ (μips · ft)

40. This value of B follows from fitting the amplitude of 100 μips at $r = 900$ ft . It is reasonable to assume that the gripper

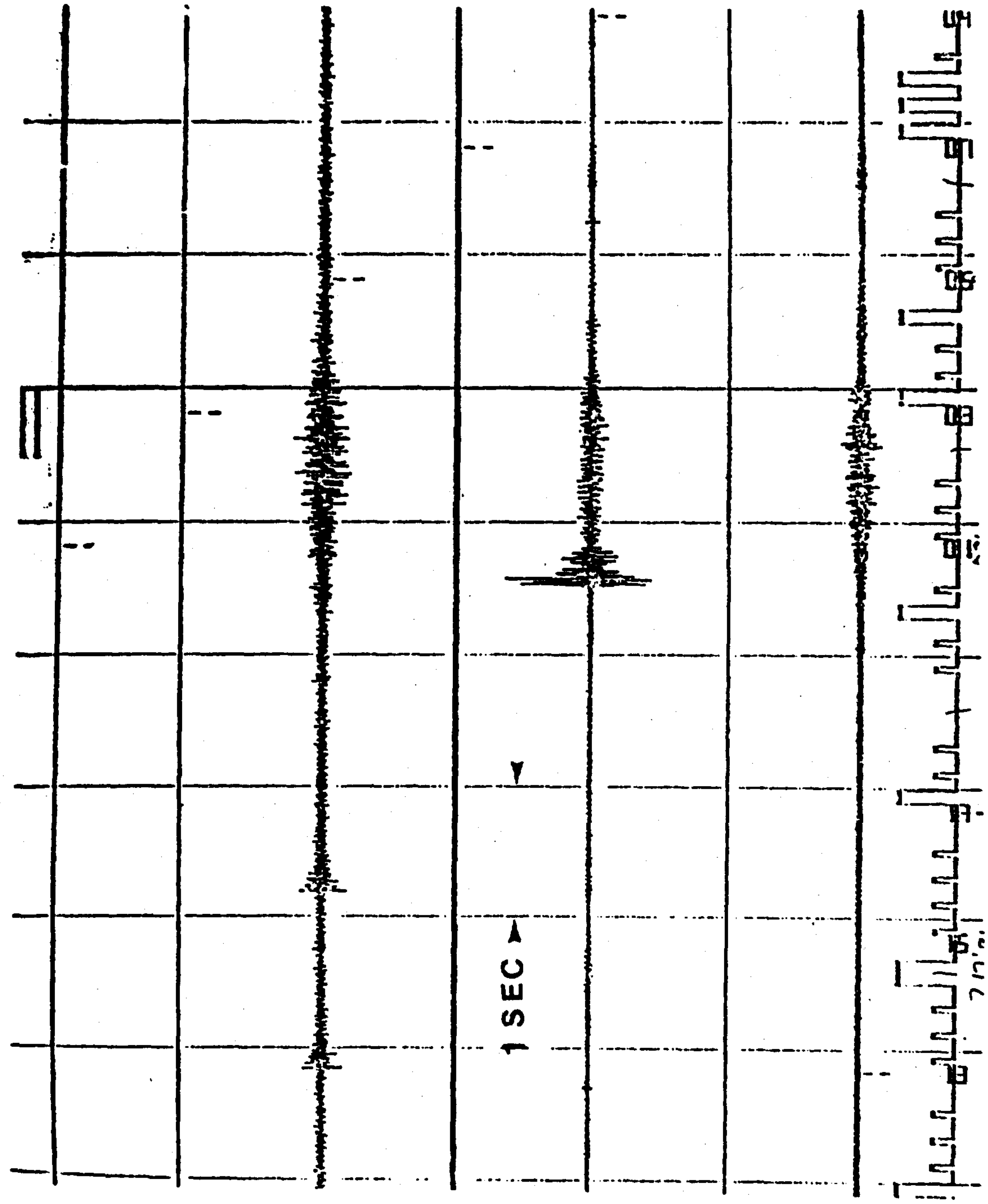

Figure 17. Gripper pads being set into old position

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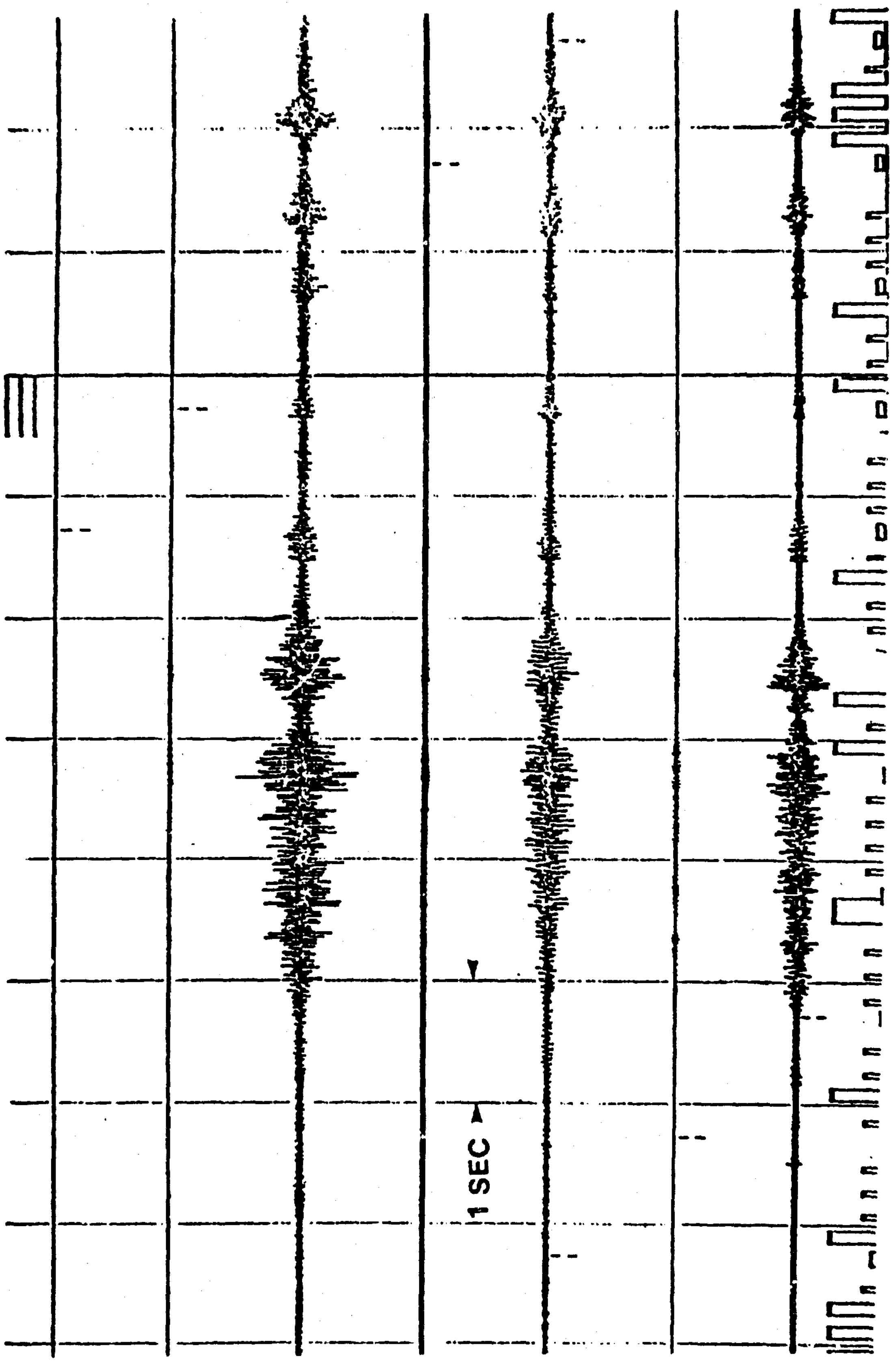

Figure 18. Gripper pads being set into fresh position

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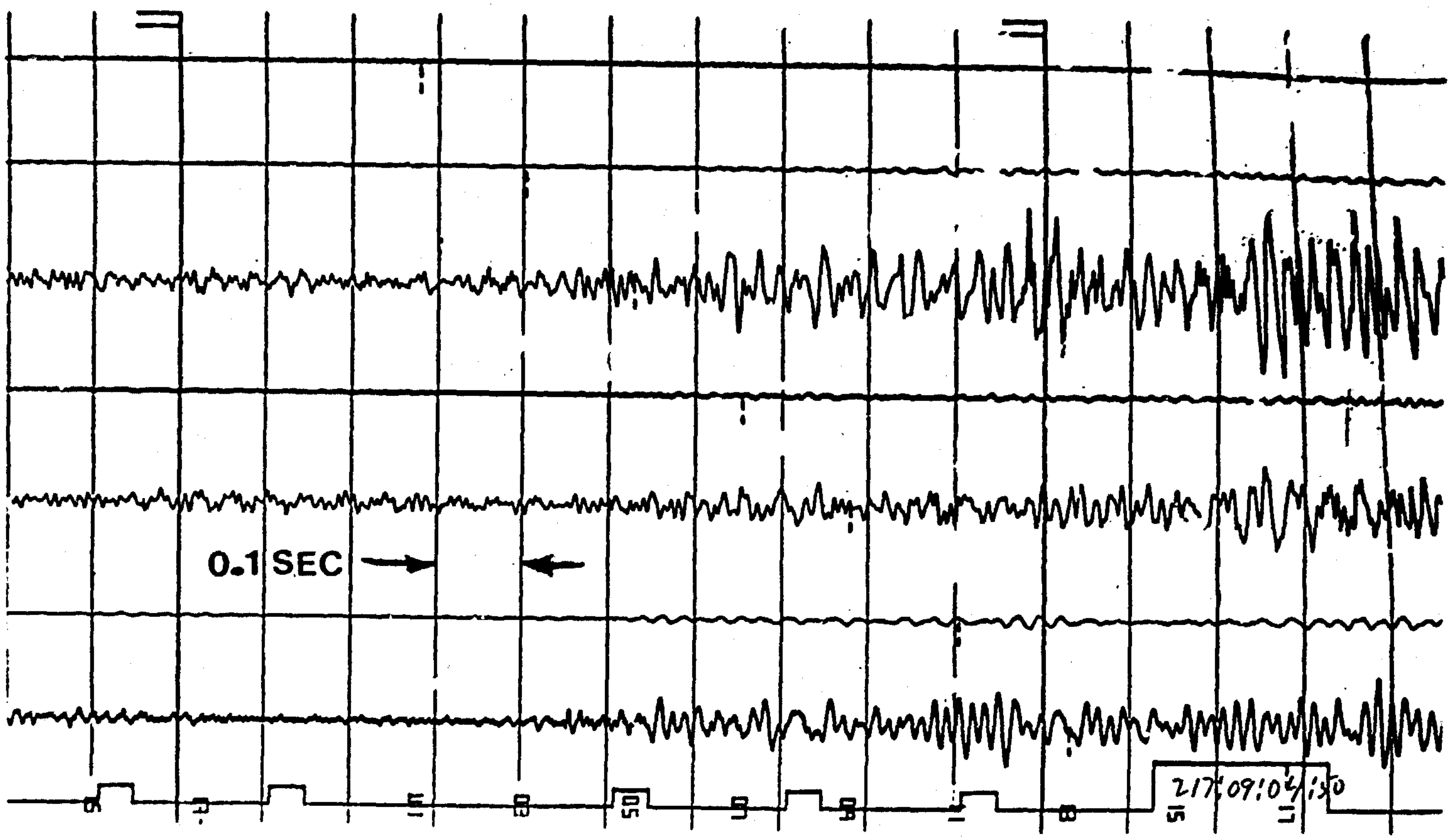

Figure 19. Gripper pads being set at fresh position, start of wave form

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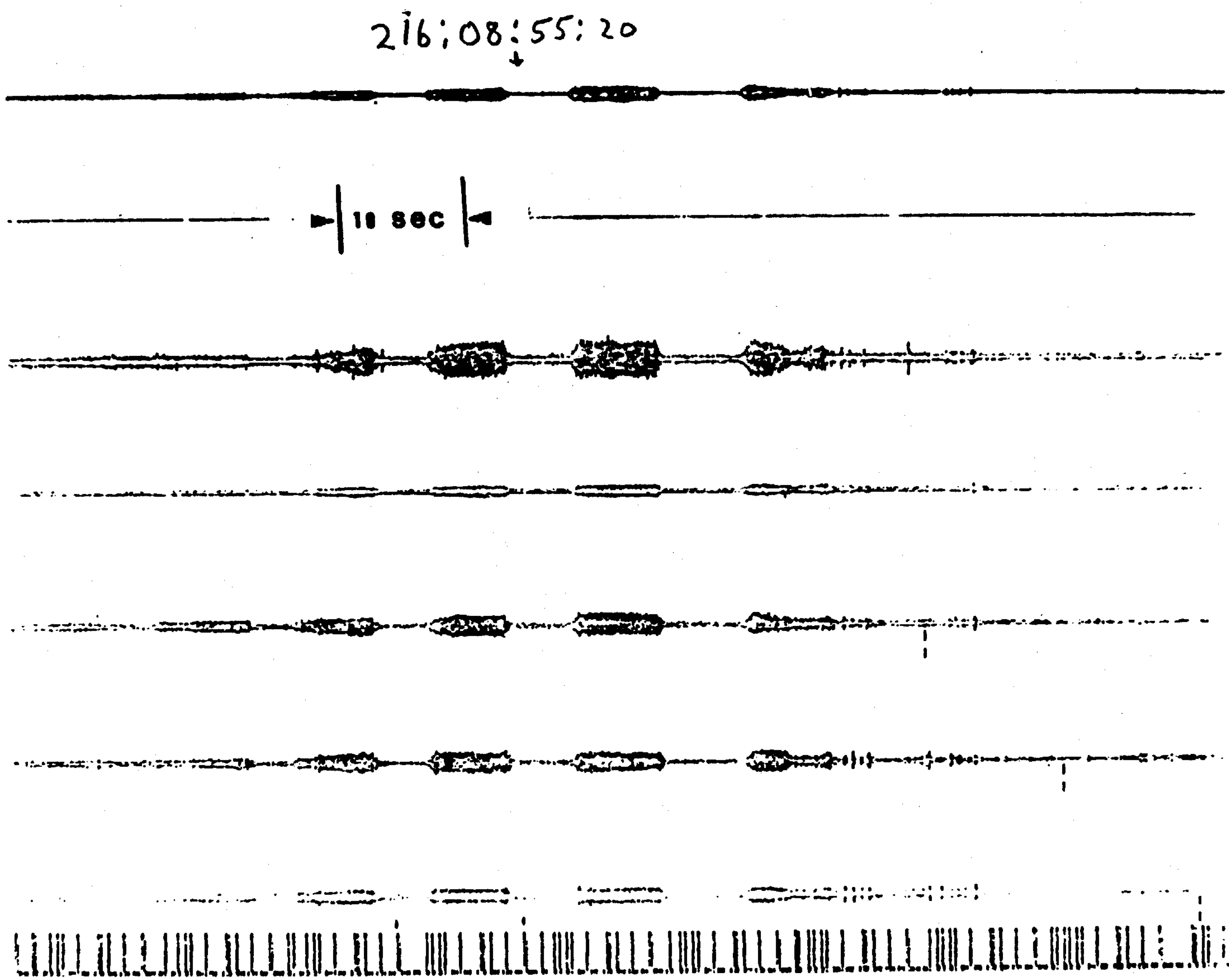
signal can be seen if the amplitude is 8 μips or greater, which is twice the measured low noise level. Under this assumption, the maximum range for detection of the gripper signal is 5453 ft. The amplitude will be 40 μips at 2138 ft, and thus at this distance, the signal will be well above noise.

41. After the TBM closed operation at 216:08:53, six examples of a particular type of harmonic seismic event were observed in a period of two minutes; the signals were observed on all subarrays. Typically, these events lasted approximately 8 sec. Records of some of these events made at three playout speeds are shown in Figures 20a, b, and c; the spectra for two events are shown in Figures 21 and 22. The events all have sharp spectral peaks. At some sites there are two spectral peaks with a 2-to-1 frequency ratio. For the event of Figure 21, the fundamental frequency is 22 Hz. The 216:08:55:12 event (Figure 22) has two spectral peaks at 14 and 28 Hz. The amplitude of the events is approximately 60 μips and stays fairly constant for the duration of an event. The harmonic nature of these events is very indicative that their source is some sort of rotating machinery. Because they occurred just after the cutting head was backed away from the face, it is reasonable to speculate that the events are caused by machinery involved in moving the head.

42. Another type of signal that appears harmonic was observed preceding and blending into the TBM start-up at 216:08:41:30; this signal appears on all the subarrays and is shown in Figure 23.



a. Slow speed playout

Figure 20. Series of harmonic events (Sheet 1 of 3)

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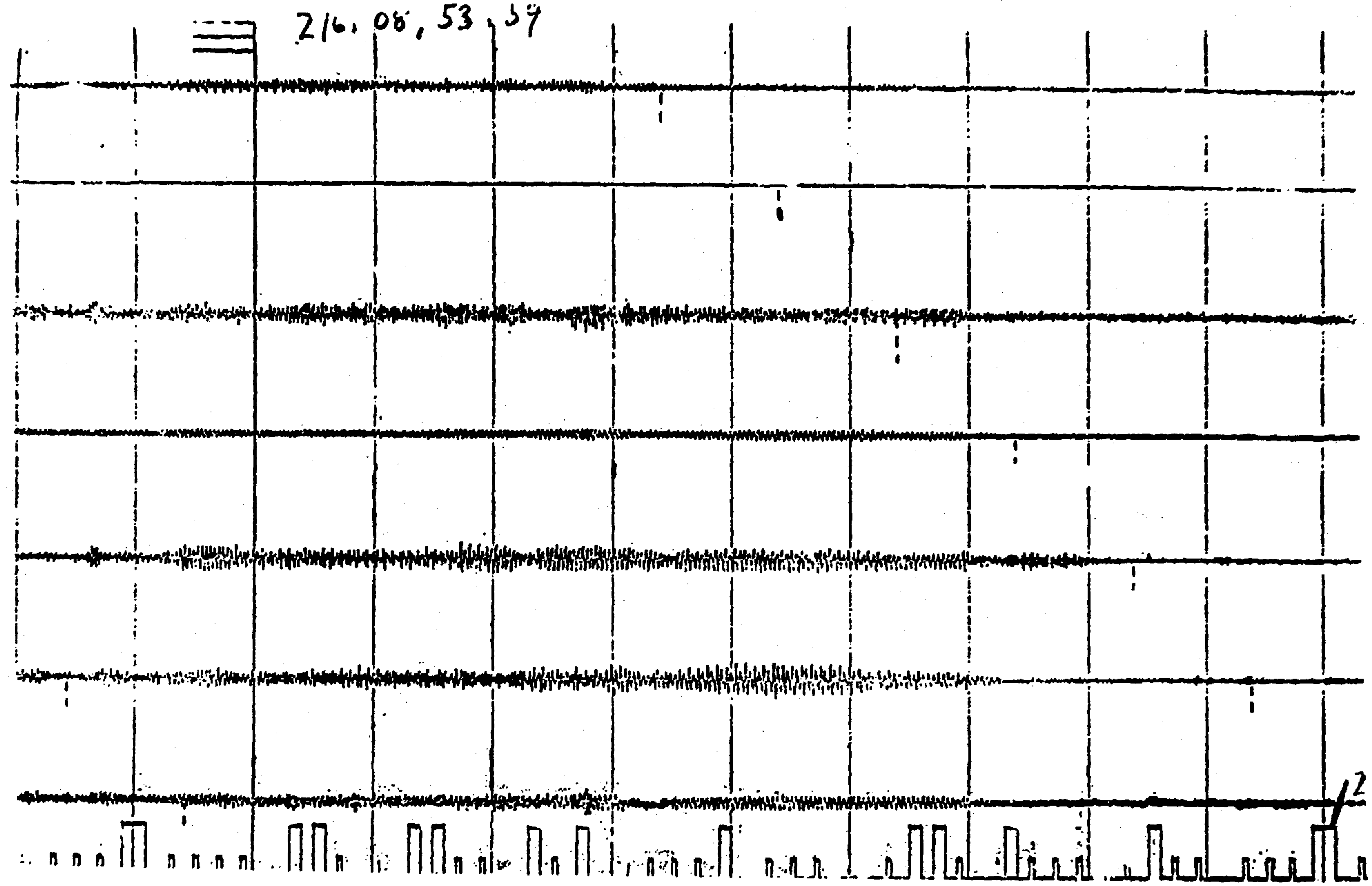

b. 1-sec timing lines

Figure 20. (Sheet 2 of 3)

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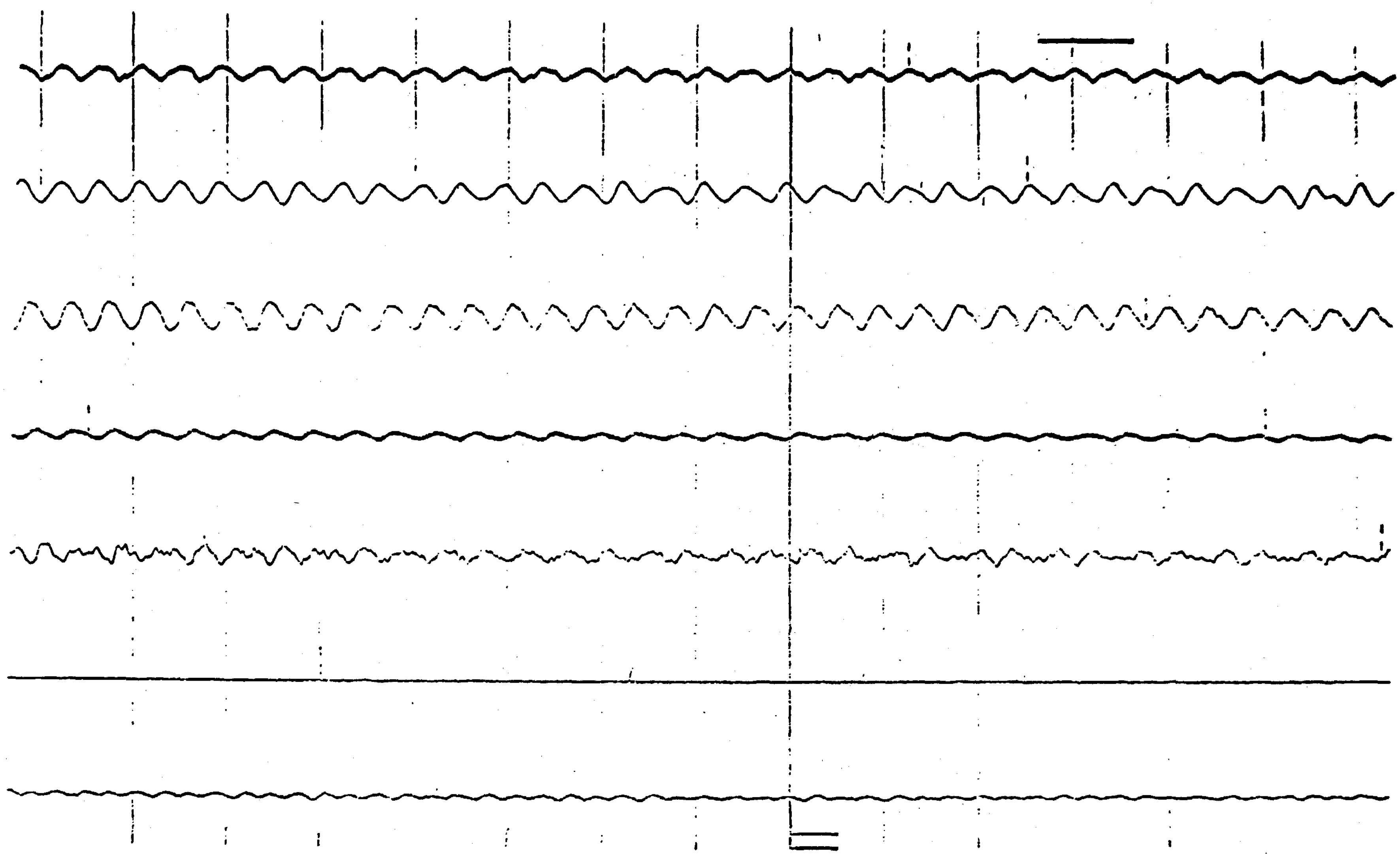

c. 0.1-sec timing lines

Figure 20. (Sheet 3 of 3)

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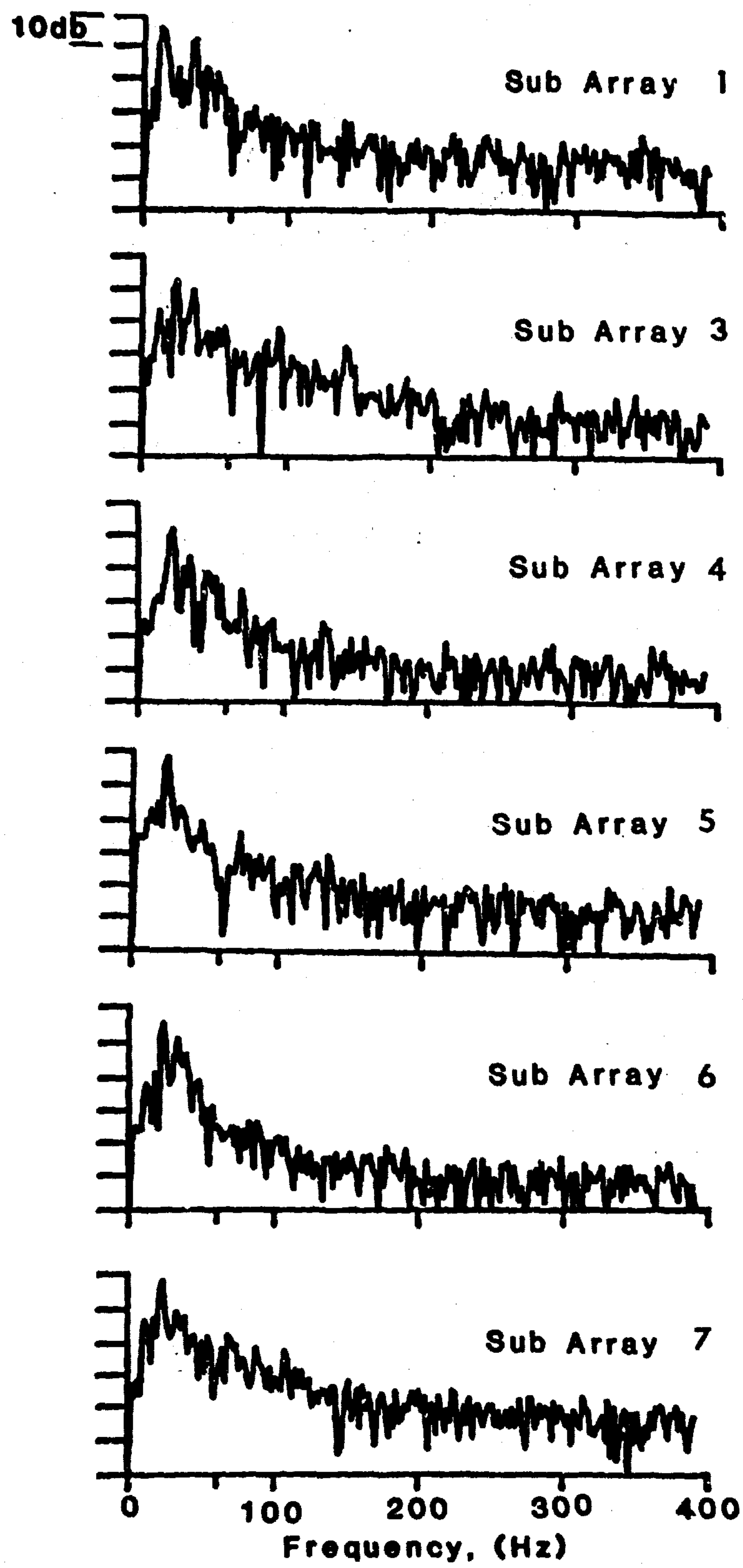

Figure 21. Spectra of harmonic event (example 1)

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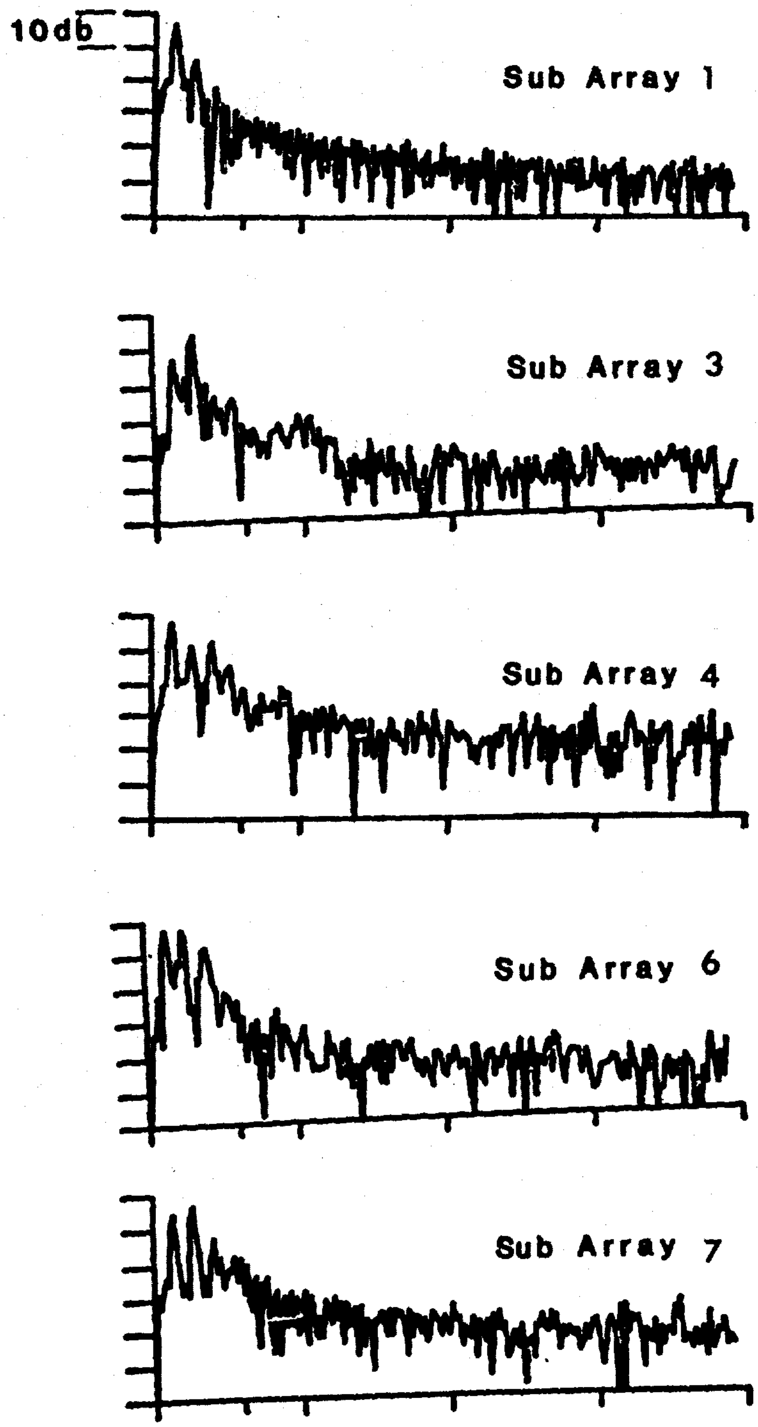

Figure 22. Spectra of harmonic event (example 2)

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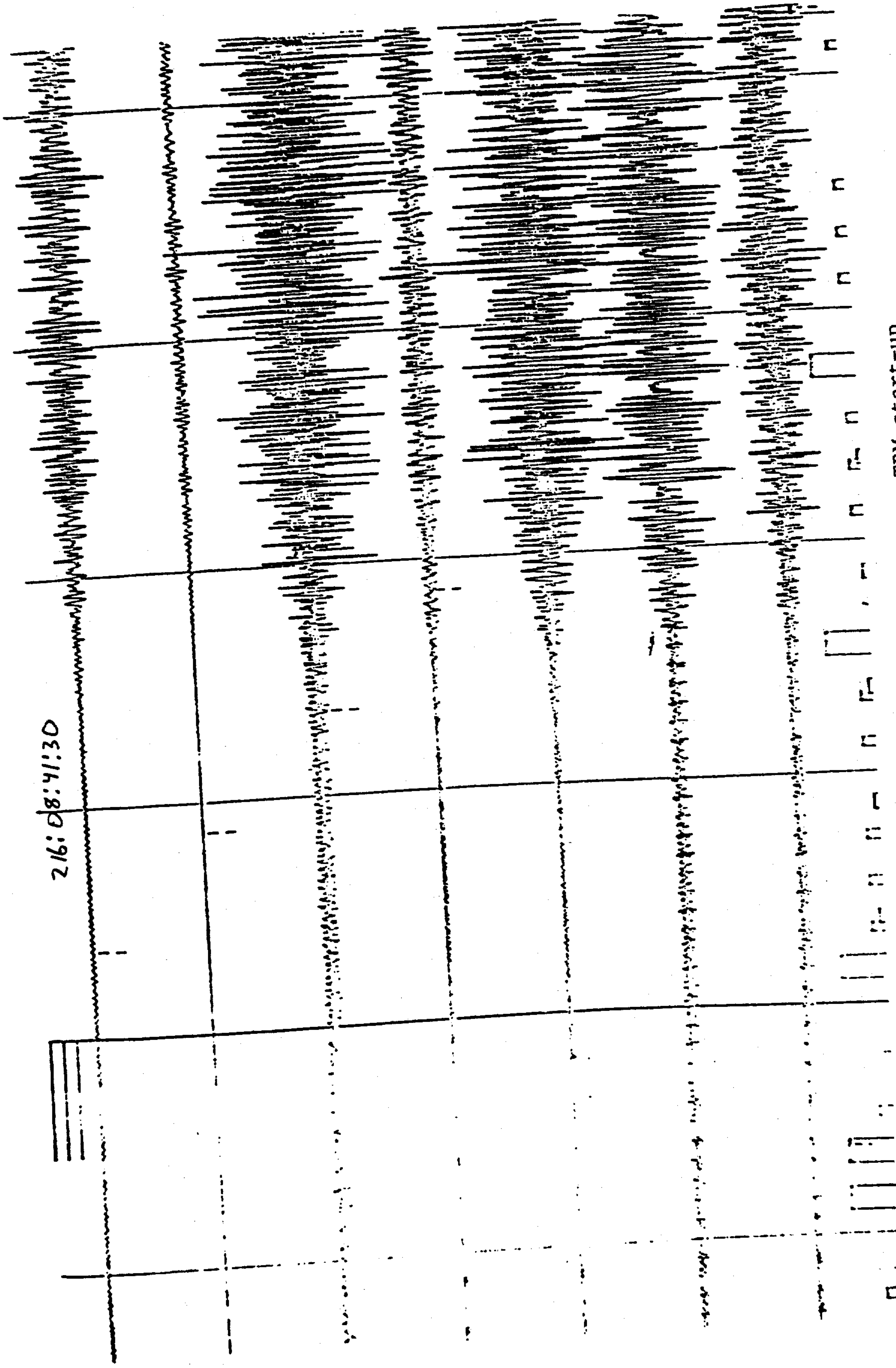

Figure 23. Harmonic event preceding TBM start-up

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PART VIII: LOCATION CAPABILITY

Velocity Determination

43. The P-wave velocity of the rock in the test area was determined by seismic refraction surveys. A normal survey with a maximum source to geophone offset of 600 ft and a survey made by recording an explosion at six subarrays with a geophone at the source was also used. The data plot for the second survey method is shown in Figure 24. Both types of refraction surveys gave a P-wave velocity of approximately 17,000 fps.

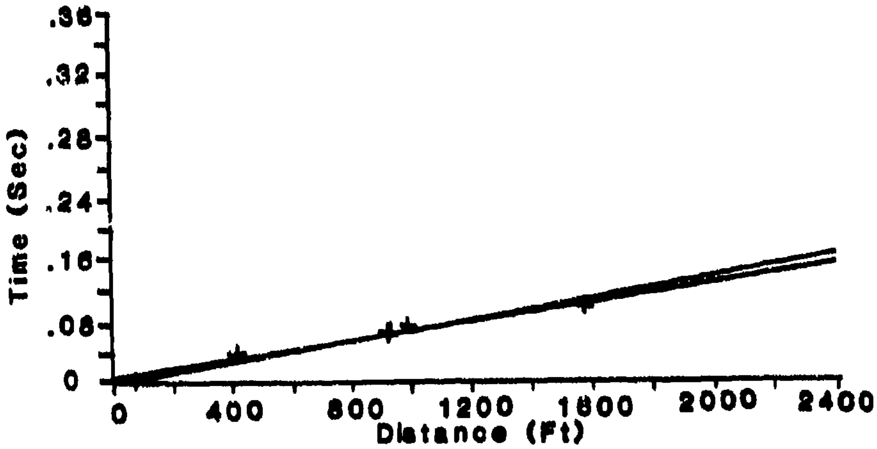

Figure 24. Refraction data and fit

Impulsive Events

44. Seismic events, with impulsive arrivals, may be located by using the relative arrival times of a signal at a number of subarrays. Two location methods are implemented on the Mine Emergency Operations Seismic Truck computer. These are the MINER method and the Least Squares Method. To use these methods, the signal arrival time must be measured to within a few milliseconds. Thus, these methods are best applied to events which start impulsively and have a clearly recognizable character, such as the signals from a miner's blow or an

explosion. One of the major purposes of this field test was to determine if a TBM gives impulsive signals suitable for location purposes.

45. The signals received from the TBM were generally not impulsive. A great deal of effort was spent looking through the records for and examining signals which might be impulsive. Many signals look impulsive on the slow speed playouts, but were not impulsive when examined on 4 ips or faster records (compare Figures 13 and 25).

46. Some events were impulsive on several channels, but not on all. Examples are given in Figures 25-28. The arrows show the start of the signal on a channel that is impulsive. For the event of Figure 24, channels 3, 6, and 7 and perhaps 4 have start times that can be read to a few milliseconds. On the other channels the event is emergent. Since a number of events were impulsive on some channels, it is possible that by observing events over a long period of time, events that are impulsive on most or all channels will be found.

47. The reason that the signal is impulsive on some channels and not others may relate to the radiation pattern of the source. It is probable that the impulsive start may be the P-wave. If the P-wave is small, it cannot be seen in the coda of previous events. The difference in wave form between the channels can also be due to differences in the geology at the subarrays. The soil and rock velocities are very different so the soil layer causes ringing of signals (see Durkin and Greenfield, 1981). There was very steep topographic relief at most subarrays. This relief can cause waves to bounce around causing later parts of the seismic wave form, from an event, to be much greater in amplitude than the first motion.

48. It may be possible to use the stacking of several events from the same source to bring out first arrivals on the emergent channels. The repeated events are time-aligned using the times on an impulsive channel. This procedure has worked well for processing repeated blows in the MSHA trapped miner field tests.

49. There were three events, which occurred between 217:09:03:03 and 217:09:03:04, and had similar wave forms on the six subarrays which were in operation at the time. A slow-speed playout of the time period

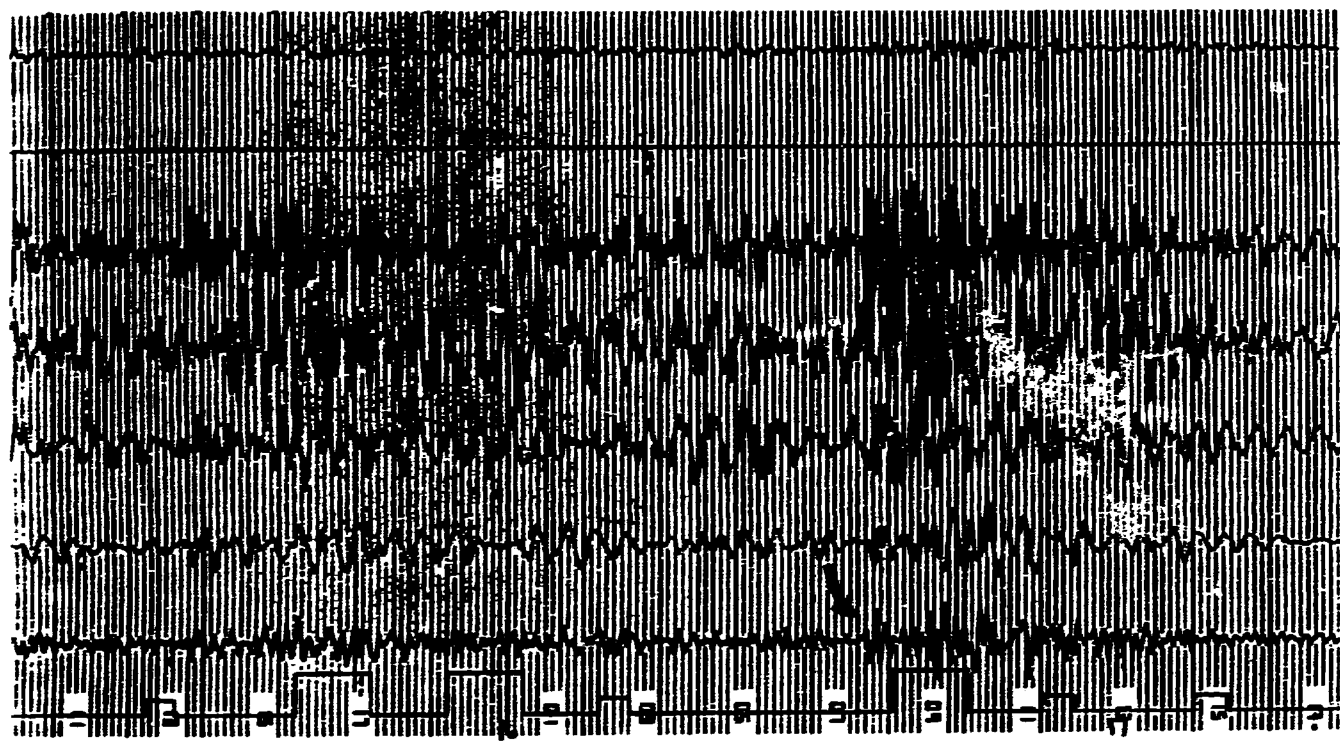

Figure 25. Event which is impulsive on some channels (example 1)

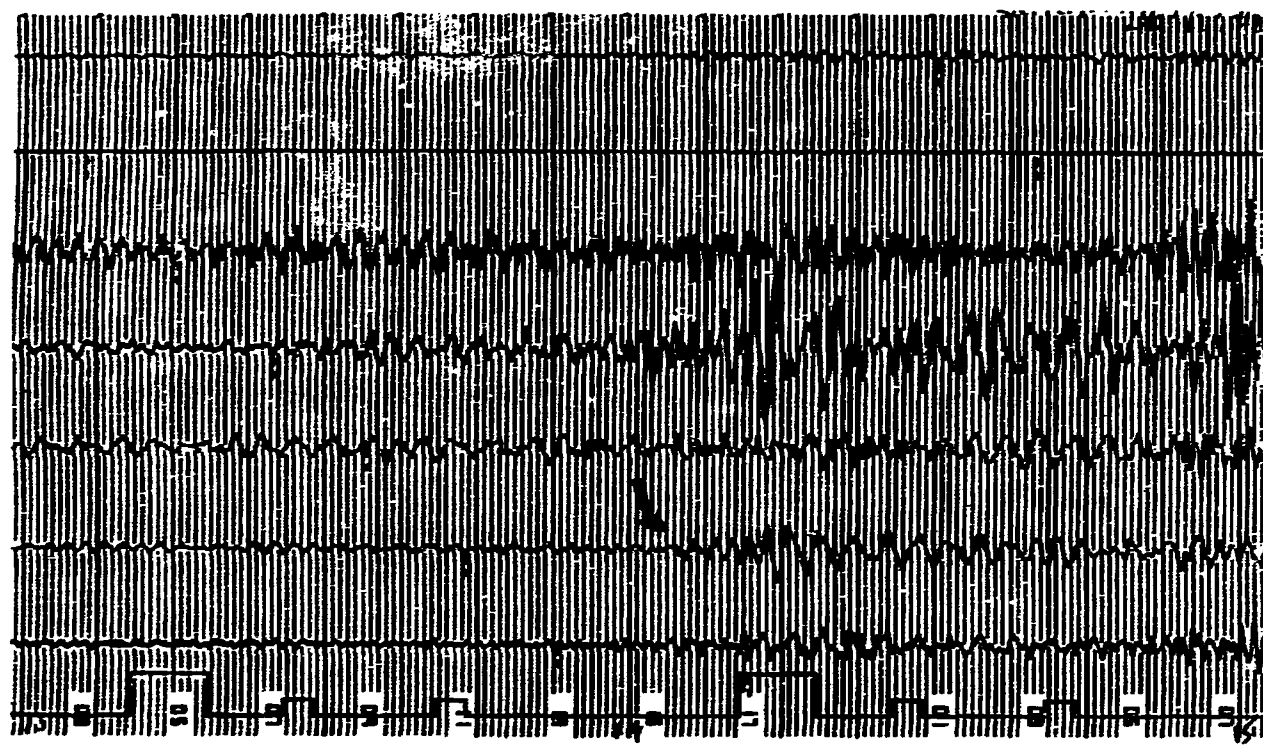

Figure 26. Event which is impulsive on some channels (example 2)

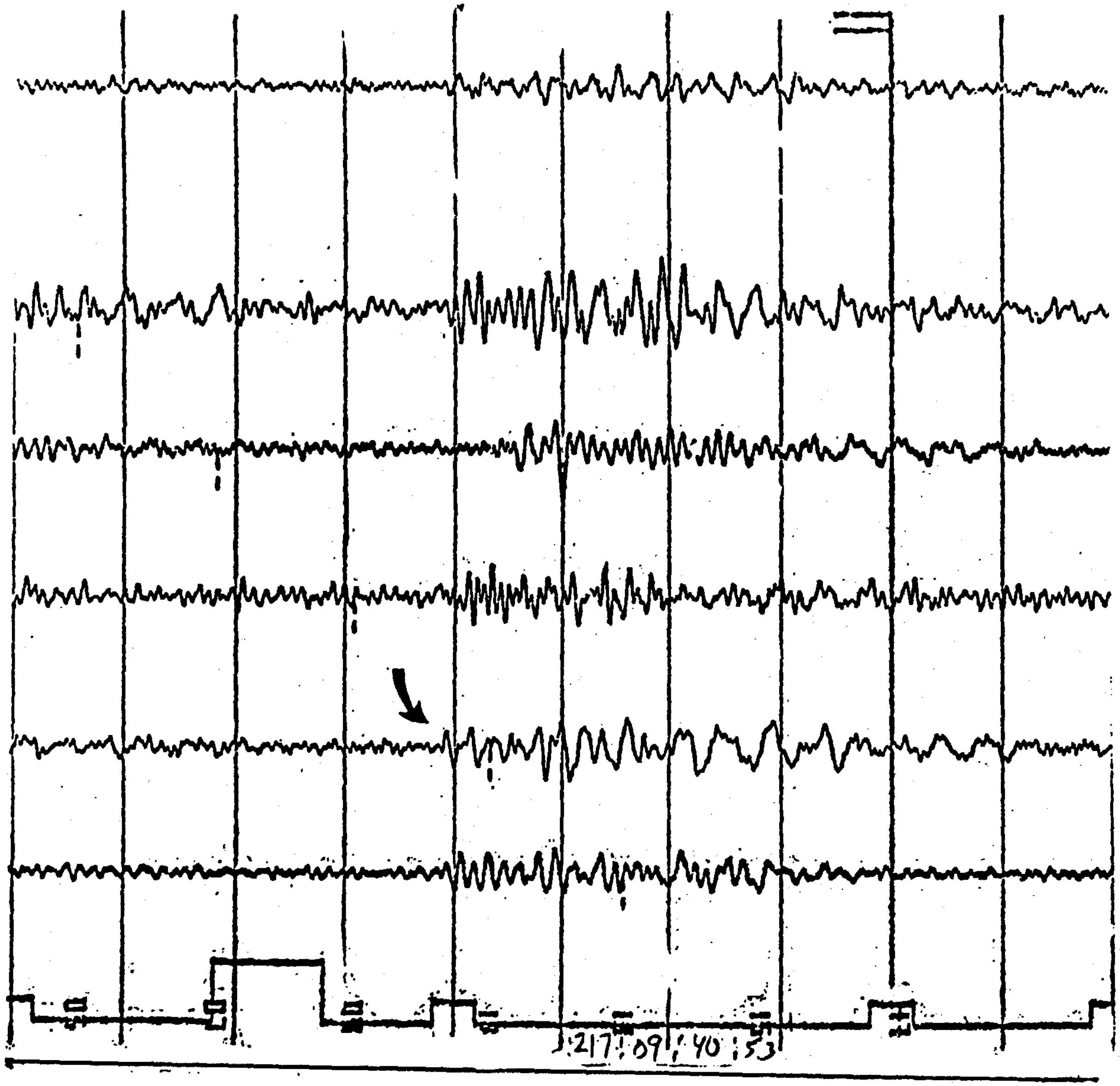

Figure 27. Event which is impulsive on some channels (example 3)

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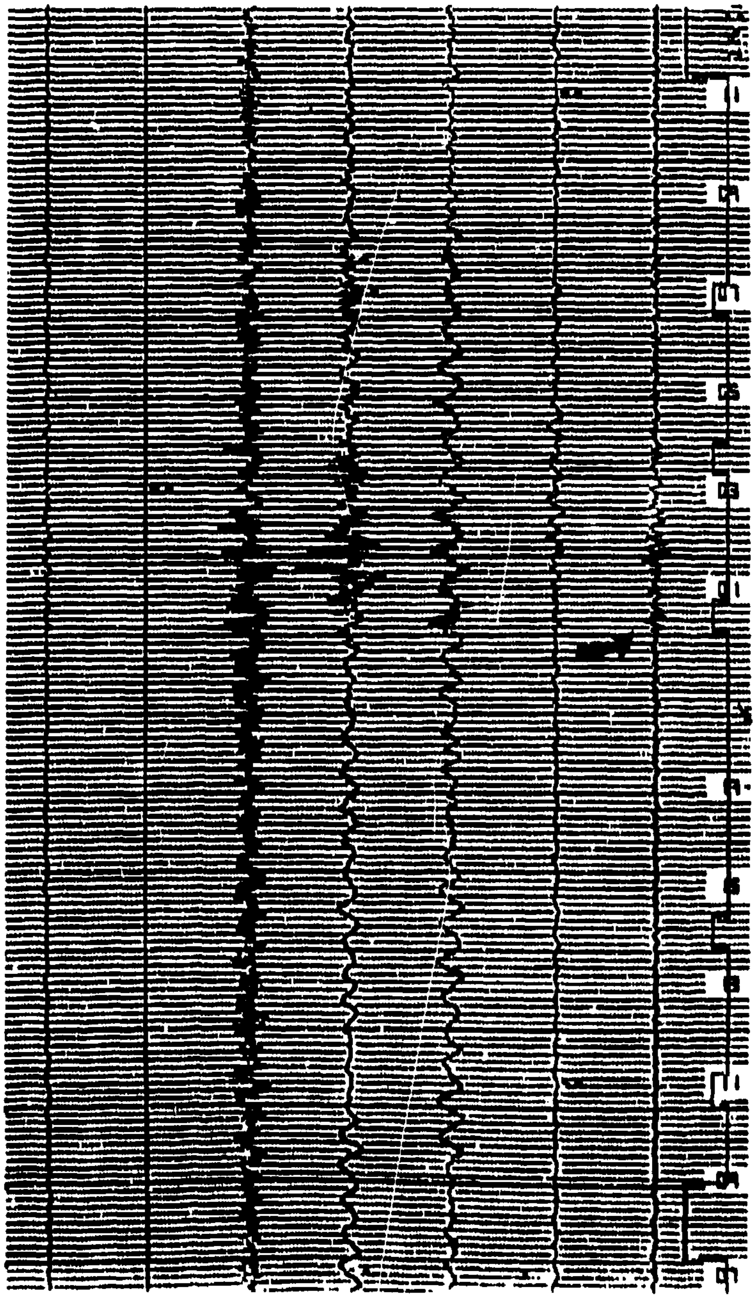

Figure 28. Event which is impulsive on some channels (example 4)

is shown in Figure 29. The group of events occurred approximately 3 min after the TBM was backed off from the face. These events occurred at the time that the motor clutch was released and the cutting head comprised of 57 cutter bits stopped turning (J. Koester,* personal communication).

50. Two methods were used to estimate relative arrival times at the subarrays for the first and largest of these events, which will be denoted as the 217:03:03 event. The first method was to pick a peak that seemed to correlate between the six subarrays and make an "eyeball" pick; these eyeball picks are marked by arrows on Figure 30, and listed in Table 2, with the arrival at subarray 4 used as the reference time.

Table 2

Arrival Time Picks, Referenced to Location 4 (msec)

Location	Eyeball	Cross Correlation
2	0	0
3	10	14
4	0	0
5	10	10
6	10	10
7	10	10

51. The second method to pick relative arrival times was to form a time domain cross correlation between the record for a master subarray and the other subarray records. A peak of the cross correlation gives the arrival time. To implement this, the data were digitized and are shown in Figure 31. The results of the cross correlation with subarray 4 as the master subarray (CH4 on the figure) are shown in Figure 32. To get the estimate of the relative arrival times between subarrays, the time difference between the peak of the cross correlation of subarray 4 with itself and the peak of the cross correlation of subarray 4 with the other five subarrays was used. The peaks used are marked on the figure. For accuracy the times were read from the computer printout of the cross-correlation function rather than measured on the

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* J. Koester, Earthquake Engineering and Geophysics Division, Geotechnical Laboratory, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

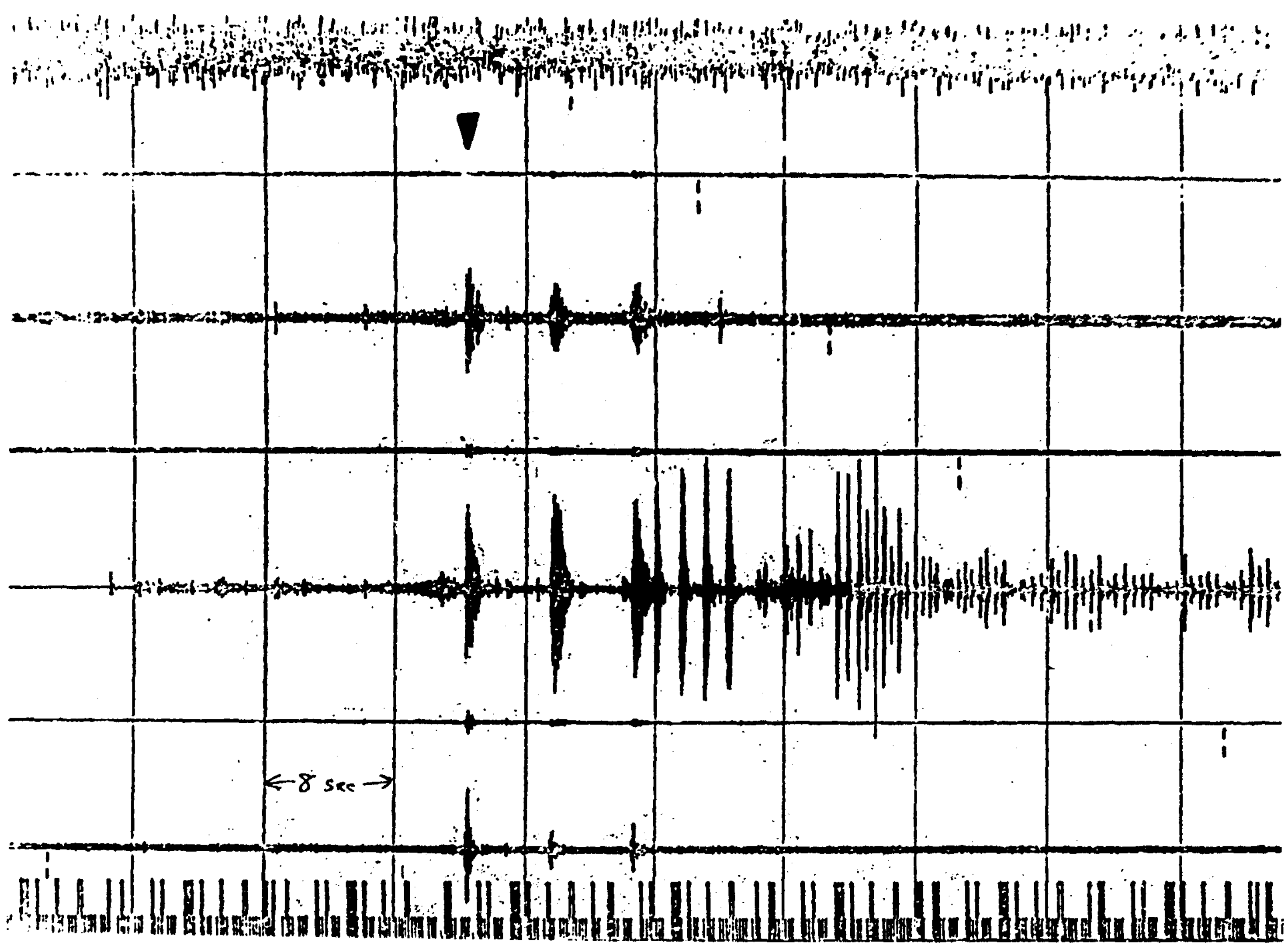

Figure 29. Series of events occurring when motor was shut off. Arrow shows 217:09:03:03 event that was located

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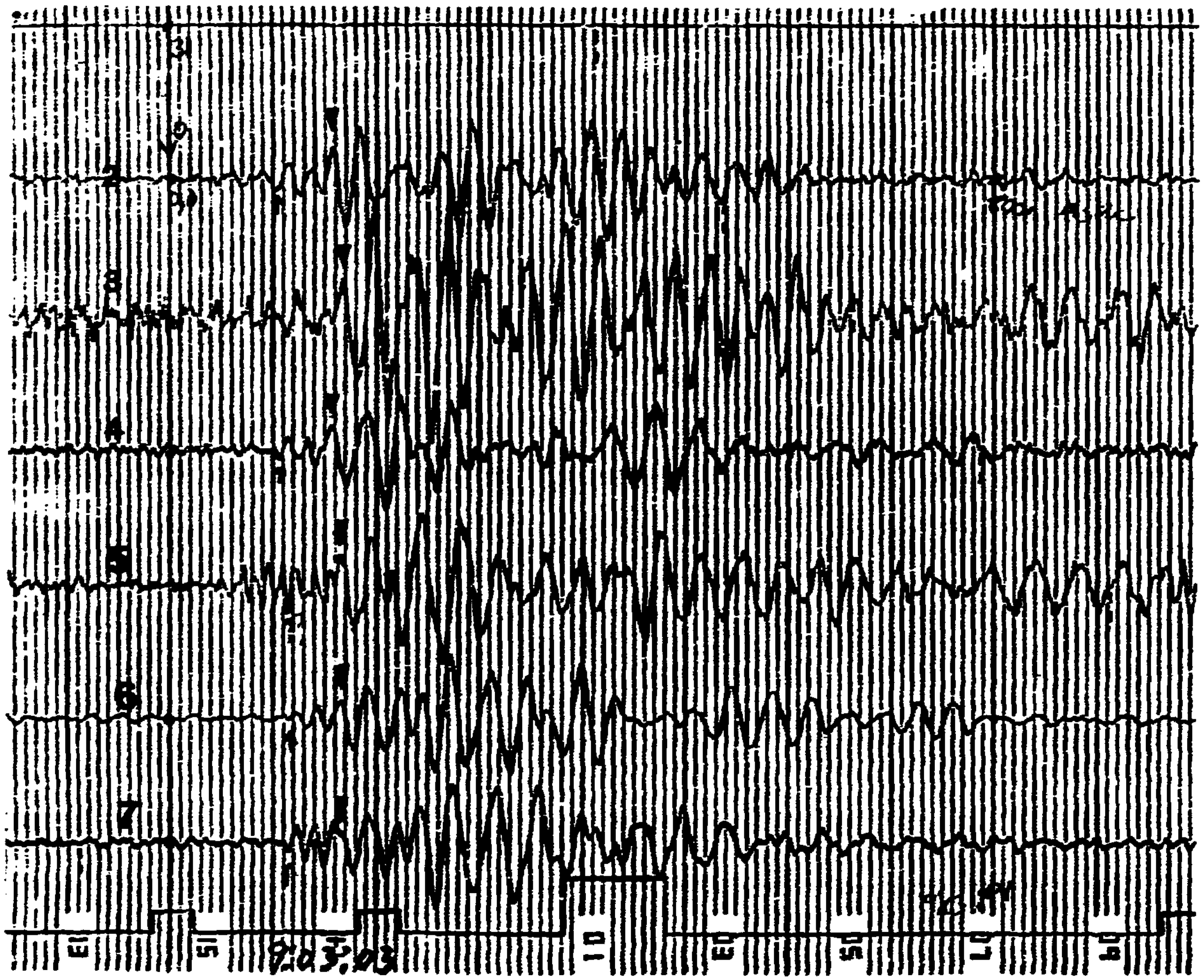

Figure 30. Record of 217:09:03:03 event. Heavy timing lines are 0.1 sec. Arrows show "eyeball" time picks

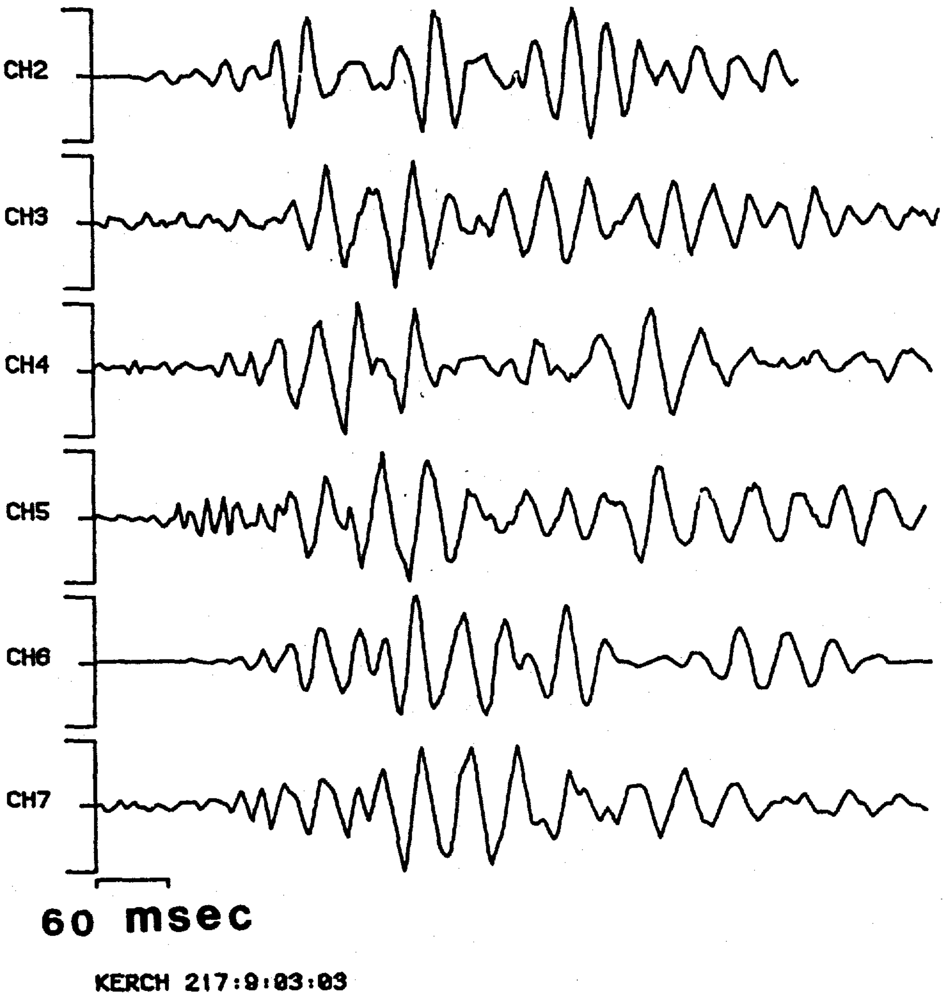

Figure 31. Digitized version of the 217:09:03:03 event

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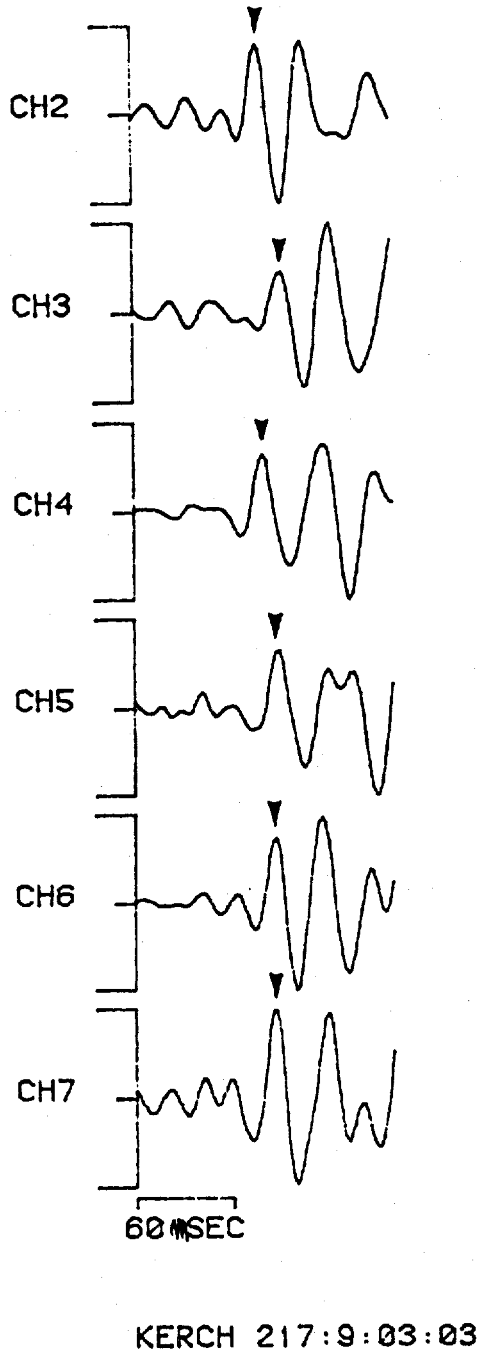

Figure 32. Cross correlations with ch 4. Channel numbers give subarray locations

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figure; this gave a precision of 2 msec. The arrival times obtained from the cross-correlation method were similar to the eyeball picks as given in Table 2 and were used in the location calculation.

52. The locations were calculated using the MINER and Least Squares methods. The locations determined are given in Table 3. The locations given are in the coordinate system with the origin at subarray 4. The location of the TBM at the time of this event was directly below subarray 4 (R. Kunz,* personal communication).

Table 3

Location Results for the 217:09:03:03 Event

Method	Fitting Velocity fps	Error North ft	Error East ft	Horizontal Error ft	Comments
MINER	17,000	70	113	135	Depth fit, 8 combinations
MINER	17,000	52	159	167	Depth not fit, 5 combinations
MINER	15,000	91	8	91	Depth not fit, 2 combinations
MINER	25,000	132	237	271	Depth not fit, 11 combinations
Least Squares	17,000	107	99	146	Depth not fit

53. To make an estimate of how accurately a source could be located with the six subarrays used for the 217:9:03:03 event, a statistical procedure was used. This method computes the 95 percent fiducial confidence ellipse. This ellipse is calculated on the assumption of random, uncorrelated arrival time of errors with a root-mean-square error of 3 msec. The interpretation of the ellipse is that if the true location is at the center of the ellipse, then the location determined by the Least Squares procedure will lie in the ellipse 95 percent of the time. Further details of the procedure are given by Evernden (1969) and Christy (1982). Results using the statistical procedure are displayed,

*R. Kunz, Auburn Constructors.

in plan view, in Figure 33. Each cross represents the axes of the 95 percent fiducial confidence ellipse for a true source location at the cross center. This plot shows that the locations are most accurate inside the array. At the center where the 217:9:03:03 event was located, the procedure gives ellipse semiaxes of just over 200 ft. The errors in the location calculated by the different procedures, as given in Table 3, are of the order predicted by the statistical procedure. The errors are somewhat larger than are normally obtained by the seismic location system (see Durkin and Greenfield, 1981). The probable causes of these larger errors are the high rock velocity which will cause a larger location error for given arrival time errors and the fact that the array radius of 900 ft was considerably less than the tunnel depth of 1311 ft.

Nonimpulsive Events by Array Processing

54. When a source emits signals continuously, it is often not possible to associate individual arrivals between subarrays. Or if individual impulsive arrivals can be associated between subarrays, the general high level of other signal arrivals does not allow sufficiently accurate determination of the arrival time to employ the MINER or Least Squares method. To get useful location accuracy, the arrival times must be accurate to a few milliseconds (see Figure 33). Most of the TBM signals were continuous and thus unsuitable for these methods. Even most individual events which appeared impulsive at slow-record speeds of 1 ips or slower were observed to be unsuitable when higher speed playouts were examined.

55. The direction towards a continuous signal source from a subarray may, however, be obtained using array-processing methods. These include frequency domain methods, called frequency-wave number methods (f-k methods) (e.g.,Lacoss et al., 1968; Lacoss et al., 1969; or Liaw and McEvilly, 1979) and time-domain methods (e.g., Capon et al., 1968; or Page et al., 1979). These array-processing methods measure the direction and speed at which wave energy is moving across a subarray.

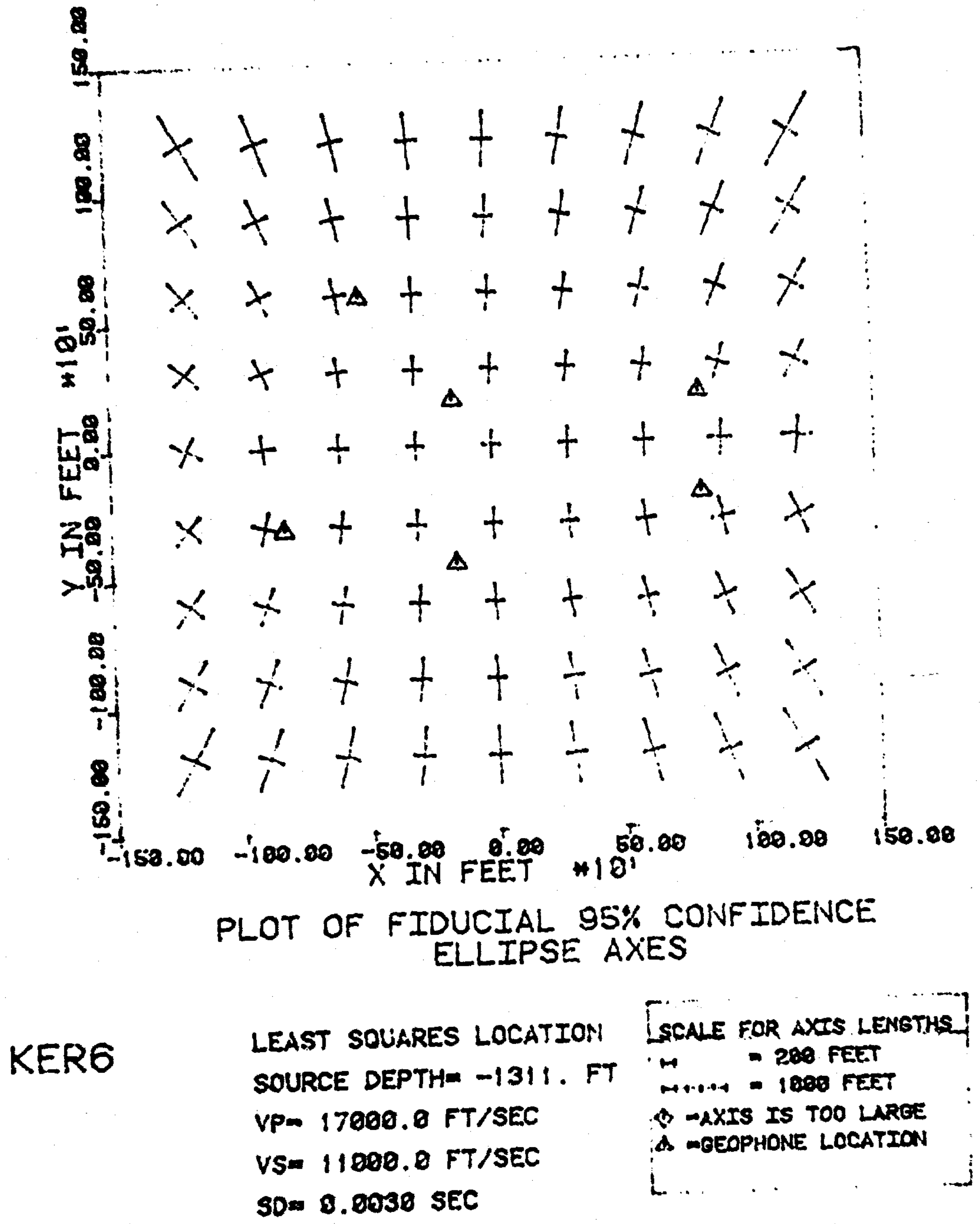

Figure 33. Plan view of fiducial 95 percent confidence ellipse axes

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In the time domain, a delayed sum or steered beam is formed in many directions and the output energy is used to estimate wave direction and speed. In the frequency domain, the phase difference between sensors is used.

56. For these array-processing methods to work, it is necessary that the continuous signal be coherent between the geophones of the subarray, and the output of the geophones must be individually recorded for computer processing. To determine if the TBM continuous signal was coherent, an experiment was performed on the afternoon of 5 August. A special subarray was set up at the location of the original subarray No. 7. This position is offset horizontally approximately 800 ft from the TBM. The plan view of this special subarray is shown in Figure 34; the geophones were recorded separately.

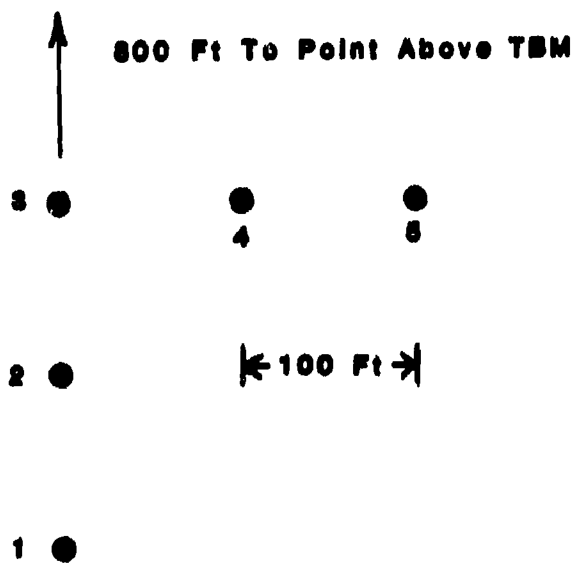


Figure 34. Plan view of special, individually recorded subarray

57. An intuitive explanation of coherency is that it is a measure of what fraction of two geophone outputs are related. For a detailed discussion of coherency, see Koopmans (1974). The relation between coherency and seismic array signal to noise gain is given in Capon et al. (1967). For a perfect coherency of 1.0, two signals must be identical to within a constant scale factor and a time shift. In the

frequency domain, the coherency $C_{ij}(f)$ between the i^{th} and j^{th} geophones is defined as

$$C_{ij}(f) = \frac{|\hat{P}_{ij}(f)|}{\sqrt{\hat{P}_{ii}(f) \cdot \hat{P}_{jj}(f)}} \qquad (4)$$

where

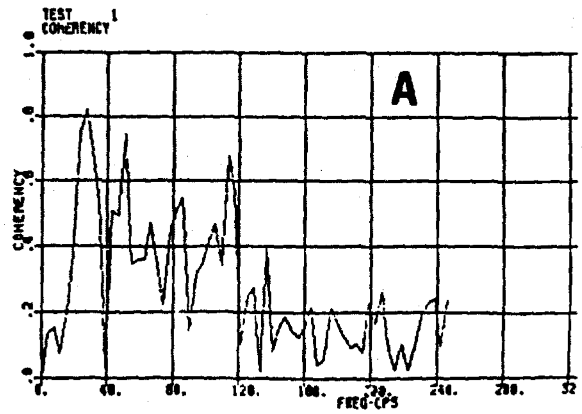
$\hat{P}_{ij}(f)$ = estimates of the cross power spectral density between the i^{th} and j^{th} geophone

f = frequency

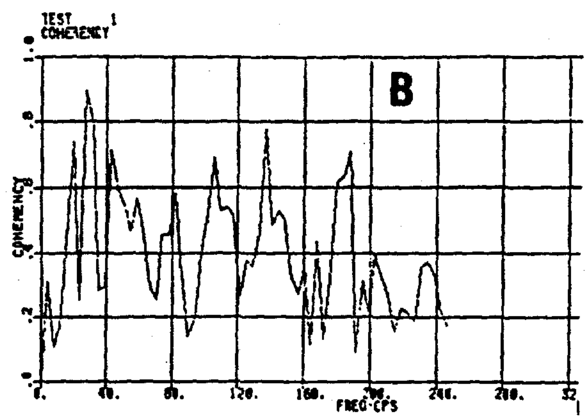
58. The frequency domain coherency can be considered to be a measure over time of the consistency of the phase, at the frequency, f, between the two records. A $C_{ij}(f)$ less than 1.0 shows that some portion of one of the signals cannot be predicted from the other.

59. Coherencies were calculated in the manner described by Capon et al. (1967, 1968), using the block-averaging method to estimate the cross power spectral density matrix. Each block was 256 msec long, so the spectral resolution was 3.9 Hz. Sixty blocks were used. Based on the statistical analysis given by Koopmans (1974), an estimated coherence above 0.17 is significant at the 90 percent confidence level. For an estimated coherence of 0.4, the lower end of the 90 percent confidence interval is 0.3. Figure 35 shows the results for the coherency between the geophones at locations 1 and 4 which were 224 ft apart. These signals are significantly coherent for most frequencies from 20 to 120 Hz. Figure 35 also shows the coherencies for geophone pairs (locations 2 and 4 and locations 3 and 4). In these cases also, the trace coherencies are 0.4 or above over much of the frequency range of 20 to 120 Hz. The coherency between all pairs of geophones was generally similar to the three coherency curves presented.

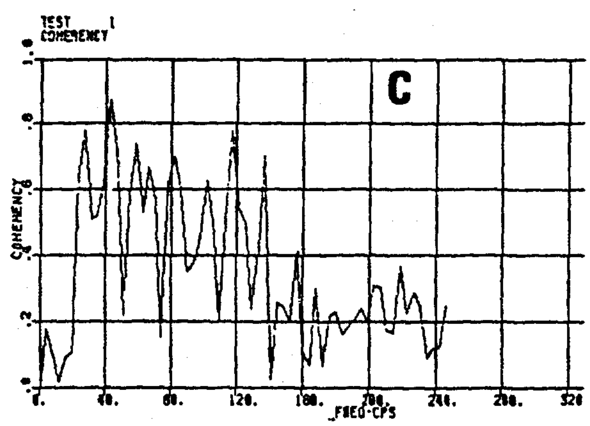
60. The statistically significant nonzero coherencies indicate that array methods can be applied to the determination of the direction from a seismic subarray towards the TBM. The coherencies were significant at frequencies to 120 Hz or more for sensor applications up to



a. Locations 1 and 4



b. Locations 2 and 4



c. Locations 3 and 4

Figure 35. Coherency plots

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280 ft. Thus, it is reasonable to discuss location in terms of individually recorded subarrays that use frequencies up to 120 Hz and have a diameter of 400 ft or more.

61. The directional accuracy that can be obtained with a subarray using published subarray response patterns in f-k space is estimated. Let k_N and k_E be the north and east wave numbers in cycles/ft (e.g., Lacoss et al., 1968, 1969). On the k_N-k_E diagram shown in Figure 36, a wave with a wave number k_C propagating at a direction β from north is plotted at $k_E = k_C \cdot (\sin \beta)$, $k_N = k_C \cdot (\cos \beta)$. Here k_C is f/C , C is the horizontal phase velocity of the wave. For a beam with wave number = k_C which is aimed north, the resolution of the beam, at the "A" db down level is denoted by k_A . For a typical subarray such as that shown in Figure 37 with diameter, D , there is a relationship between D and the resolution in wave number of the form

$$D \cdot k_A = G \tag{5}$$

where G is a constant determined by contouring the subarray beam pattern. If the 6 db down from peak contour is used, G will be approximately 0.6 (see Lacoss et al., 1968) for typical subarrays. The value of G is not sensitive to the details of the subarray geophone locations, only to D .

62. Thus, use

$$k_A = 0.6/D \tag{6}$$

63. To determine the angular resolution $2 \cdot \alpha$ for waves propagating at a velocity C and frequency f , Figure 36 is used to obtain the relationship

$$\frac{\alpha(f)}{2} = \sin^{-1} \left[\frac{k_A/2}{k_C}\right] \tag{7}$$

or

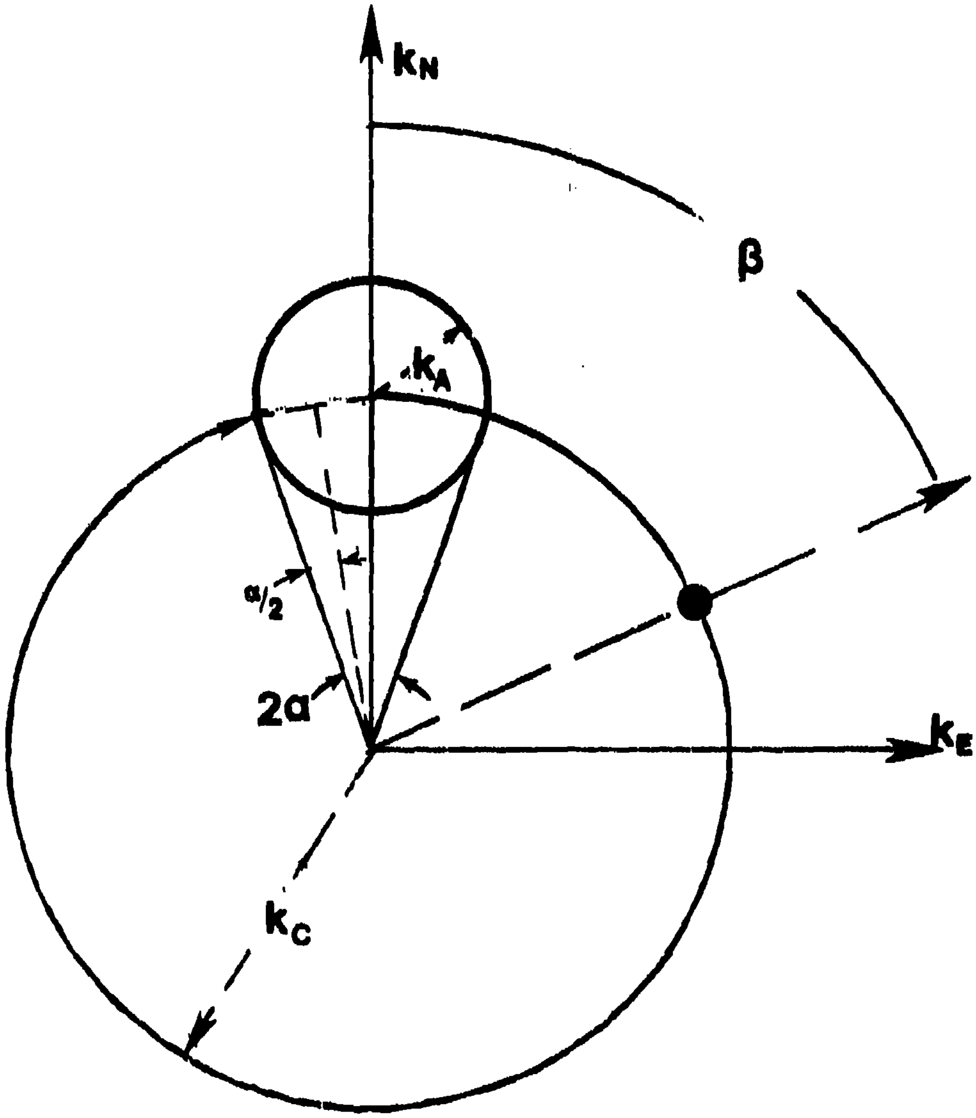


Figure 36. Wave number diagram

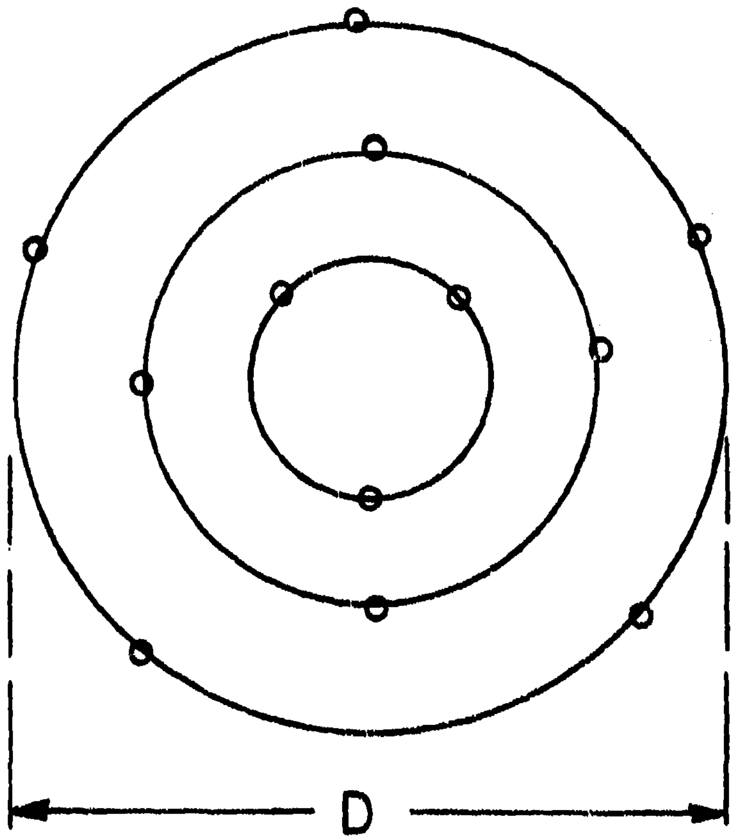


Figure 37. Sample subarray with diameter D

$$2 \cdot \alpha(f) = 4 \sin^{-1} \left[\frac{(0.6)\ C}{2 \cdot D \cdot F} \right] \tag{8}$$

64. For a concrete example, let $C = 15{,}000$ fps and D be 500 ft. Then Figure 38 shows the beam width angle, $2 \cdot \alpha$ versus f. Note the resolution improves (i.e., $2 \cdot \alpha$ gets smaller) with frequency and array diameter and degrades with C. In many previous studies, surface waves have been used in areas of sedimentary rock (e.g., Liaw and McEvilly, 1979). Since surface waves have horizontal phase velocities much smaller than 15,000 fps, these studies have generally had resolutions of 20 deg or better. At the Kerckhoff Tunnel, surface waves were not important because of the depth of the TBM and the frequency range used in the data analysis. For the slower surface waves from a

shallow source, the angular resolution would be improved from that shown in Figure 38.

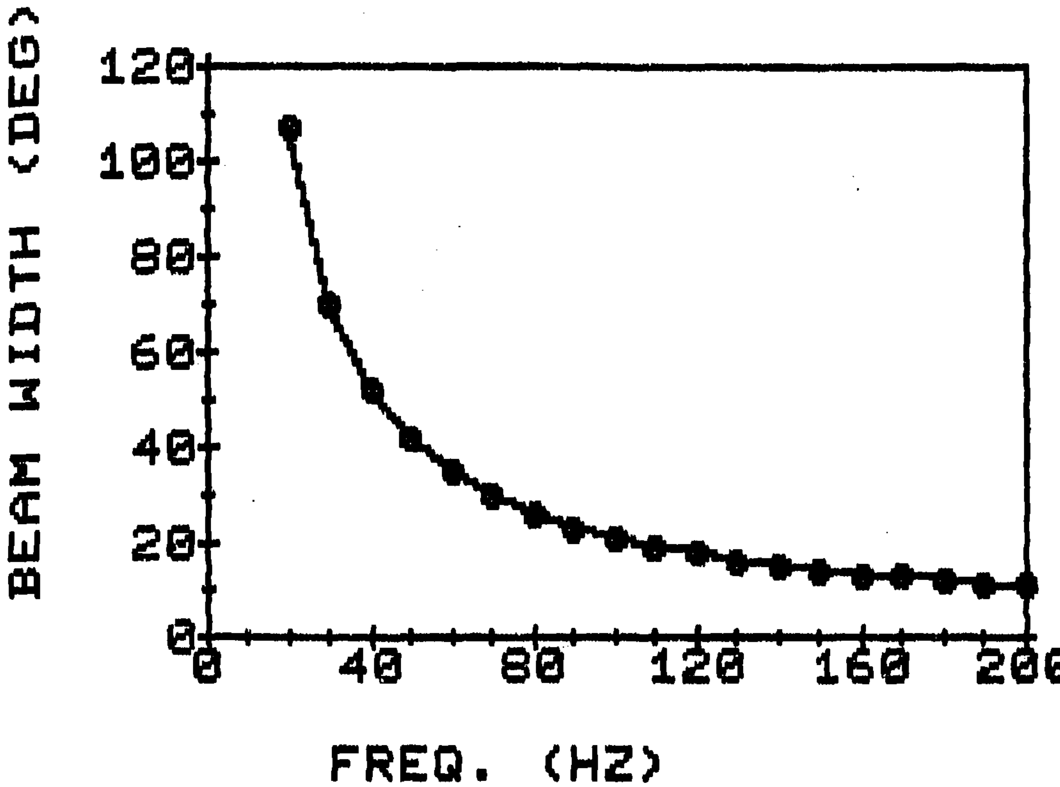
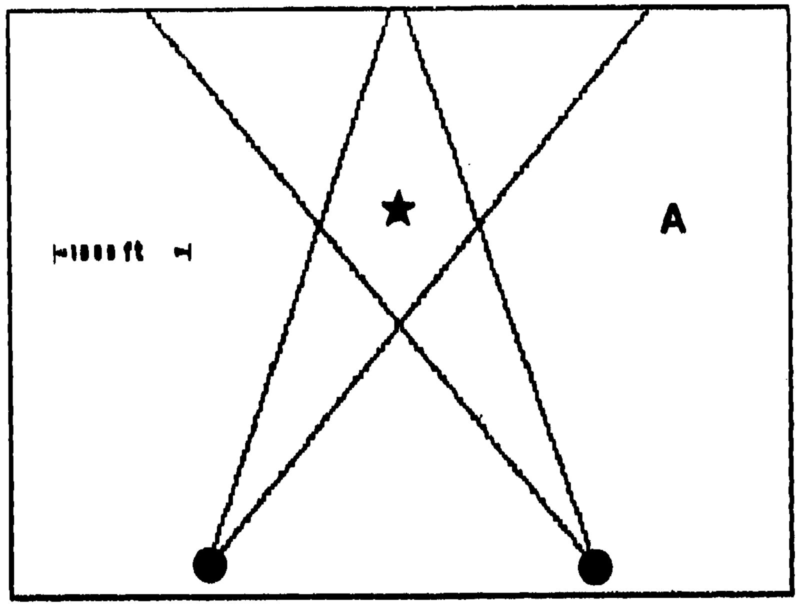
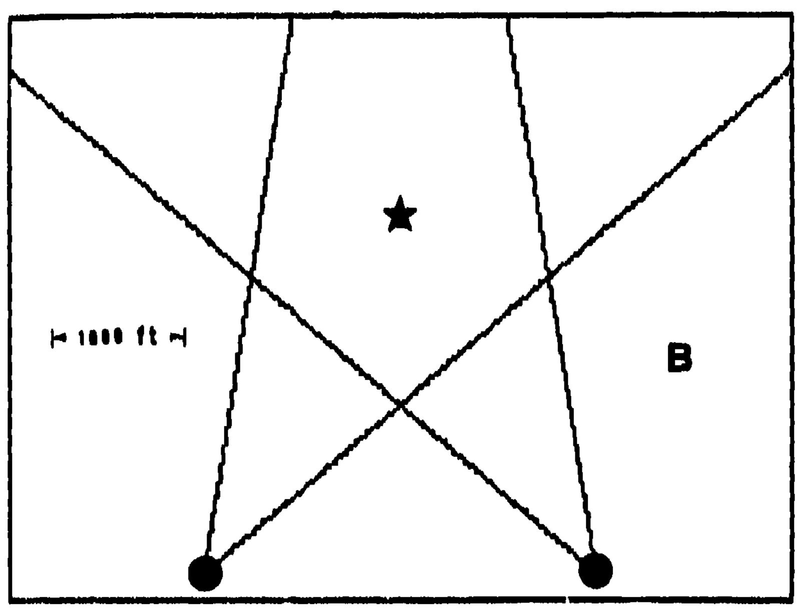


Figure 38. Beam width $2 \cdot \alpha$ versus frequency

65. To find the horizontal position of a source, the intersection of two or more beams must be considered. Figures 39 a and b show two examples which are typical of the geometry that might be used to locate a TBM. The two subarrays are separated by 3000 ft. The shaded area is the area in which the actual source could be located if the center of the two subarray beams crossed at the star. This area represents the areas of uncertainty. For the 20-deg case, the location error would, on the average, be approximately 400 ft. For this geometry, east-west accuracy is better than the north-south accuracy. For the 40-deg case, the location error will be approximately twice the 20-deg beam width.



a. 20-deg beam width



b. 40-deg beam width

Figure 39. Mapp illustrating location accuracy. Circles are special subarrays. Star is true event location. Event will be located in intersection of bemas from subarrays

66. Based on the results of the Kerckhoff Tunnel test, a preliminary description is possible for a seismic system designed to monitor a large area. This description is based on the results of this test only and must be considered only as an initial attempt to suggest a system configuration that must be reevaluated in the light of further testing. It is, however, useful to have such a configuration in mind when planning future tests and analyses.

67. The first requirement is that the system contain enough subarrays to detect tunneling activity. Figure 40 gives a hypothetical example of tunneling activity progressing towards the line A. Line A has small subarrays spaced at separations of D . These small subarrays are of the type used for the Kerckhoff Tunnel test and give a single output.

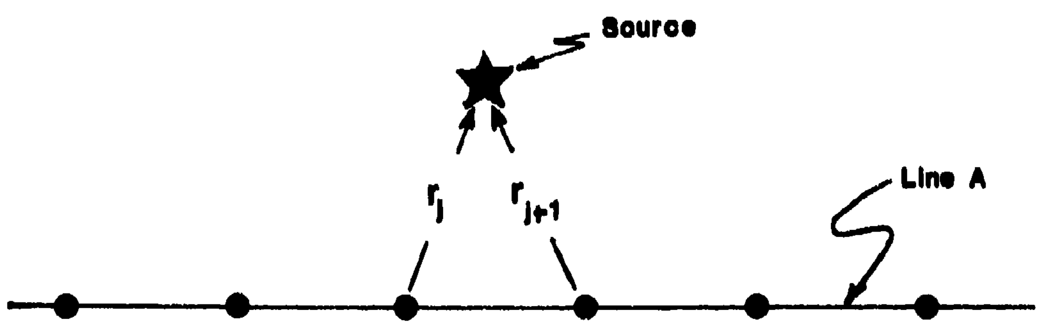


Figure 40. Illustration of a permanent seismic array to detect tunneling towards line A. Dots represent seismic subarrays

Future tests may indicate that three-component sensors should be used. For the Kerckhoff Tunnel geology and a TBM of its type, D could be as great as 10,000 ft if it is satisfactory that only one subarray is required to detect the tunneling activity. This follows since the tunnel path would have to pass at most a distance D/2 from the closest subarray, and results of this study demonstrate that a TBM of the Kerckhoff type could be detected at at least 5000 ft. However, it would be more realistic to require that at least two subarrays be in position to detect signals. This then would reduce D to 5000 ft.

However, the TBM might generate smaller signals than the Kerckhoff TBM. Thus to assure detection by at least two subarrays, a D of 2500 ft might be desirable.

68. If a tunneling detection system is to monitor for signals over a long period of time, computer-based automatic detection of activity should be considered. Such a system would look for, among other indicators, a nearly simultaneous change in seismic level or frequency at two or more subarrays. This supports the desirability of a spacing D small enough to allow two or more subarrays to detect seismic activity.

69. For use after detection of suspicious activity, a mobile seismic system should be available. The purpose of the mobile system would be to further verify the detection and to locate the source as well as possible. This system would be brought to the area of suspected activity for deployment of additional sensors. The mobile system should have the capability to deploy a number of small subarrays of the type in the MSHA system, and perhaps three of the special subarrays, with individually recorded geophones, of the type discussed in Part VIII of this report. Each of these special subarrays would have on the order of 12 individually recorded geophones.

70. The location would be done by deploying the small subarrays to surround the suspected source, if conditions allowed. The small subarrays would look for impulsive events. The special subarrays would be used either on individual impulsive events or to locate on continuous signals generated by the TBM using the array-processing methods discussed in Part VIII of this report.

PART X: SUMMARY AND CONCLUSIONS

71. The Kerckhoff Tunnel field test demonstrated that a large tunnel boring machine (TBM) can be detected using passive seismic monitoring. The TBM was at a depth of 1300 ft. At subarrays within 1000 ft of the point above the TBM, the signal amplitude is approximately 100 times the amplitude of natural noise. The TBM signal was clearly observed to distances of 5000 ft. Based on an extrapolation of data, it is probable that the TBM signal would be observable to distances between 7,500 and 10,000 ft at sites similar in geology to the Kerckhoff Tunnel site.

72. Several types of signals were observed which could be used to identify the seismic signal source as man-made. In particular, there were signals with narrow band frequency spectra, a distinct pattern at start-up and shutdown, and numerous short duration signals before start-up or after shutdown.

73. A location was determined, with an accuracy of approximately 150 ft, for one signal associated with the stopping of the TBM cutting head rotation motor. Signals from the setting of sidewall gripper pads were not impulsive enough to allow time picks sufficiently accurate for location. Numerous other impulsive events had wave forms that could be correlated on some but not all subarrays.

74. A special subarray was used to determine if array-processing methods had potential for locating TBM's if it gave only continuous signals. This subarray had five individually recorded vertical geophones in an L-shaped subarray with 200-ft legs. The coherencies measured between the geophones were statistically significant, which indicates that array processing can be used for location purposes. The accuracy of these methods was discussed.

PART XI: RECOMMENDATIONS

75. Further areas of study include the following:

- a. Further analysis of present data for possible impulsive signals for location purposes. Attempt to stack these signals.
- b. Analyze the horizontal geophone data and consider combined use of horizontal and vertical geophone outputs.
- c. Do a field test with a shallower machine, which will probably excite surface waves.
- d. Do further array processing on the special subarray data taken at the Kerckhoff test.
- e. Do a test where more careful study can be done at horizontal distances at which the TBM signal is disappearing into the noise.
- f. Take data with more geophones in a special subarray (approximately 12) for array processing.
- g. Have a voice communication link with the tunnel at future tests.
- h. Attempt to relate the TBM signal to the characteristics of the machine and geology. A better understanding of these factors will allow improved estimates of detection capability of other TBM's.
- i. Attempt to get signal data for several types and sizes of TBM's.
- j. Determine if putting geophones on bedrock improves detection capability.

76. Recommendations for a permanent seismic installation are as follows:

- a. Small subarrays of approximately 15 ft diam with the geophones added together to give one output would be used in a permanent installation.
- b. The spacing between subarrays would be 2500 ft.
- c. Digital computer based automatic monitoring should be incorporated into the system.
- d. A mobile seismic system should be available to verify the detections by the permanent installation and to locate the source.

REFERENCES

Ballard, R. F., Jr. 1982. "Tunnel Detection," Technical Report GL-82-9, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Capon, J., Greenfield, R. J., Kolker, R. J., and Lacoss, R. T. 1968. "Short-Period Signal Processing Results for the Large Aperture Seismic Array," Geophysics, 33, pp 45-472.

Capon, J., Greenfield, R. J., and Lacoss, R. T. 1967. "Design of Seismic Arrays for Efficient On-Line Beamforming," Technical Note 1967-26, Lincoln Laboratory, Lexington, Mass.

Capon, J., Greenfield, R. J., and Lacoss, R. T. 1969. "Long Period Signal Processing Results for the Large Aperture Seismic Array," Geophysics, 34, pp 305-329.

Christy, J. J. 1982. "A Comparative Study of the MINER and Least Squares Location Techniques as Used for Seismic Location of Trapped Coal Miners," M.S. Paper, Geosciences Department.

Devine J. F., Beck, R. H., Meyer, A. V. C., and Duvall, W. I. 1966. "Effect of Charge Weight on Vibration Levels from Quarry Blasting." Bureau of Mines RI 6774, Pennsylvania State University, University Park, Pa.

Durkin, J., and Greenfield, R. J. 1979. "Study of Possible Modifications to the Trapped Miner Seismic Location System," Interim Report 4268, Bureau of Mines Pittsburgh Mining and Safety Research Center, Pittsburgh, Pa.

Durkin, J., and Greenfield, R. J. 1981. "Evaluation of the Seismic System for Locating Trapped Miners," Bureau of Mines RI 8567.

Evernden, J., Jr. 1969. "Precision of Epicenter Obtained by Small Number Worldwide Stations," Bulletin of the Seismological Society of America, No. 59, pp 1365-1398.

Greenfield, R. J. 1982. "Maximum Plot Size Because of AGC," File Memo to Westinghouse Electric Company, Alliquippa, Pa.

Koopmans, L. H. 1974. "The Spectral Analysis of Time Series," Academic Press, New York.

Lacoss, R. T., Capon, J., and Greenfield, R. J. 1968. "Preliminary Design of a Long-Period Seismic Array for Norway," Technical Note 1968-4, Lincoln Laboratory, Lexington, Mass.

Lacoss, R. T., Kelly, E. J., and Toksoz, M. N. 1969. "Estimation of Seismic Noise Structure Using Arrays," Geophysics, 34, pp 24-38.

Liaw, A. L., and McEvilly, T. V. 1979. "Microseisms in Geothermal Exploration," Geophysics, 44, pp 1097-1115.

Page, E. A., Houck, R. T., and Bauman, R. W. 1979. "Geothermal Ground Noise Experiment at Old Faithful Geyser," Final Report, Enaco, Inc., Contract No. 14-08-0001-16315 to the U. S. Geological Survey.

Ruths, M. A. 1977. "The Reference-Correction Method for Improving Accuracy in the Seismic Location of Trapped Coal Miners," M.S. Thesis, Pennsylvania State University, University Park, Pa.

Siskind, D. E., Stagg, M. S., Kopp, J. W., and Dowding, C. H. 1980. "Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting," Bureau of Mines RI 8507.

Stagg, M. S., and Engler, A. J. 1980. "Measurement of Blast-Induced Ground Vibrations and Seismograph Calibration," Bureau of Mines RI 8506.

Westinghouse Electric Corporation. 1971. "Coal Mine Rescue and Survival, Col 2: Communications Location Subsystem," Bureau of Mines Contract HO-101-262.

APPENDIX A: SEISMIC LOCATION SYSTEM FIELD TEST

MINE EMERGENCY OPERATIONS PROGRAM

AUGUST 1982

SEISMIC LOCATION SYSTEM FIELD TEST

Pacific Gas and Electric Company
and
Auburn Construction Company
Kerckhoff #2 Project
Auberry, California

July 31 thru August 6, 1982

SUMMARY REPORT

CONTRACT J2725001

Prepared for:

U.S. Department of Labor
Mine Safety and Health Administration

Prepared by:

Westinghouse Electric Corporation
Mine Emergency Operations
1613 Knecht Avenue, M.S. 6030
Baltimore, Maryland 21227

"The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Department of Labor's Mine Safety and Health Administration".

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1.0 INTRODUCTION

Test number three of the four field tests provided under Contract J21725001 took place at the Kerckhoff #2 Project near Auberry, California. Testing was accomplished during the period July 31, 1982 thru August 6, 1982. This is a report detailing the test activity and the results of the field test.

During the first of this year's field tests at the Hamilton #1 Mine in Morganfield, Kentucky, representatives of the U.S. Army Corps of Engineers were on-site to witness the performance of the Seismic Location System. The Corps had expressed interest in the Seismic System as a means of detecting tunnel construction.

As a result of the Corps' interest, the decision was made to select a tunnel under construction and conduct a field test at that construction site.

The Kerckhoff #2 Project is a tunnel 24 feet in diameter and approximately 5 miles long. It is being bored by means of a tunnel boring machine, which is essentially a 24-foot diameter horizontal drill. The tunnel is being cut through granite and has approximately 1300 feet of overburden at the selected test site.

The following statement of test objectives and tasks to be accomplished during this field test/demonstration were mutually agreed between MSHA and the U.S. Army Corps of Engineers.

"<u>Objective</u>: Determine the ability to detect noise from the boring machine; and the maximum range and accuracy of MSHA seismic detection system when deployed to locate tunneling operations.

"The MSHA is requested to provide the labor, materials, and equipment required to perform field tests at a site located near Fresno, CA. The following specific work tasks were performed:

"Task 1 - Perform an on-site reconnaissance and take the legal steps necessary to obtain site access. Select the first listening area centered above the location of the tunnel boring machine (TBM) and survey the locations of the subarrays of the seismic detection system. Establish a working relationship with on-site personnel of the contractor (Auburn Construction Company) and the client (Pacific Gas and Electric Company).

"Task 2 - Mobilize and transport MEO equipment to test site. Emplace the system and acquire data from the first location over TBM. Process data on site for "quick look", target signature, and location. At times when the TBM is not in operation, conduct other tests using hammers, pick blows, and/or other devices which might simulate tunneling by other methods.

"Task 3 - Relocate the subarrays to greater distances from TBM operation. The actual relocation spots will be determined by on-site analysis of the data obtained during Task 2. Perform refraction seismic surveys at each subarray location at a time most advantageous to field-operating conditions. Repeat data acquisition procedure outlined in Task 2.

"Task 4 - Relocate subarrays to a third position which will be selected as result of evaluation of on-site analyses of all previous data obtained. Repeat previous test sequence for data acquisition.

"Task 5 - Perform a separate test using individually recorded geophones within each subarray and/or conduct special tests devised on-site by Dr. Roy Greenfield.

"Task 6 - Provide "back home" support for analysis of all test data which will be performed by Dr. Greenfield.

It is expected that the above program should be performed over a period of approximately five days during the first half of August 1982. The actual dates will be established during the on-site reconnaissance as dictated by coordination with the Auburn Construction Company and PGE. It must be understood that the work will be performed on a noninterference basis with the construction schedule."

Permission to use the area as a test site was obtained from Pacific Gas and Electric Company and the Auburn Construction Company, and MEO personnel visited the site from July 19 thru July 22, 1982 to make arrangements with the two companies and to choose a test site.

Part of the MEO team returned to the Fresno-Auberry area on July 27 to obtain access to the operating area and to have the subarray locations surveyed. The remainder of the team, with the vehicles, arrived in Fresno on July 30, 1982.

On-site observers sponsored by the U.S. Army Corps of Engineers included the following:

Mr. Robert Ballard	WESGH USA Corps of Engineers
Maj. Bill Norton	WESGH USA Corps of Engineers
Mr. Joe Koester	WESGH USA Corps of Engineers
Mr. Don Grogan	MERADCOM USA
Mr. John Bowman	MX Officer Norton AFB USAF
Mr. Dave Edwards (TRW)	Representing the BM Office USAF

2.0 SEISMIC TEST SUMMARY

2.1 CHRONOLOGY

On July 31, 1982 the MEO crew arrived at the test site. The survey results, showing the subarray location coordinates, had been obtained from the surveyor's office the previous day. These location coordinates are listed in Table 1.

By the end of the first day, the geophone subarrays had been located, the Seismic System had been checked out and was functioning well, and everything was ready for testing which was to begin on Monday, August 2.

Unfortunately, by Monday morning a brush fire which had started several miles away on Saturday, was threatening the entire test area. All of the subarrays were recovered and the area was evacuated.

By Tuesday, August 3 the fire had been brought under control and everything was set up and checked out again. Some testing was accomplished Tuesday evening, and the remainder of this test was completed by Friday morning August 6, 1982.

The test site was vacated by Friday evening, and the MEO team returned to Fresno prior to departing for the next field test.

Relocation of subarrays as prescribed in Task 3 and 4 could not be accomplished entirely because of topography. However, seismic listening, using the refraction survey equipment, was conducted at several locations and distances from the tunnel site as the crew was departing from the operating area.

TABLE 1

SUBARRAY LOCATIONS

Kerckhoff #2 Project

Subarray	North Coordinate	East Coordinate	Elevation
1	517,480	5046511	2163
2	517,592	505,454	2179
3	516,689	504,837	2215
4	517,178	505,513	2211
5	516,549	505,517	2217
6	517,816	506,484	2145
7	516,798	506,486	2153

Note: All distances are in feet.

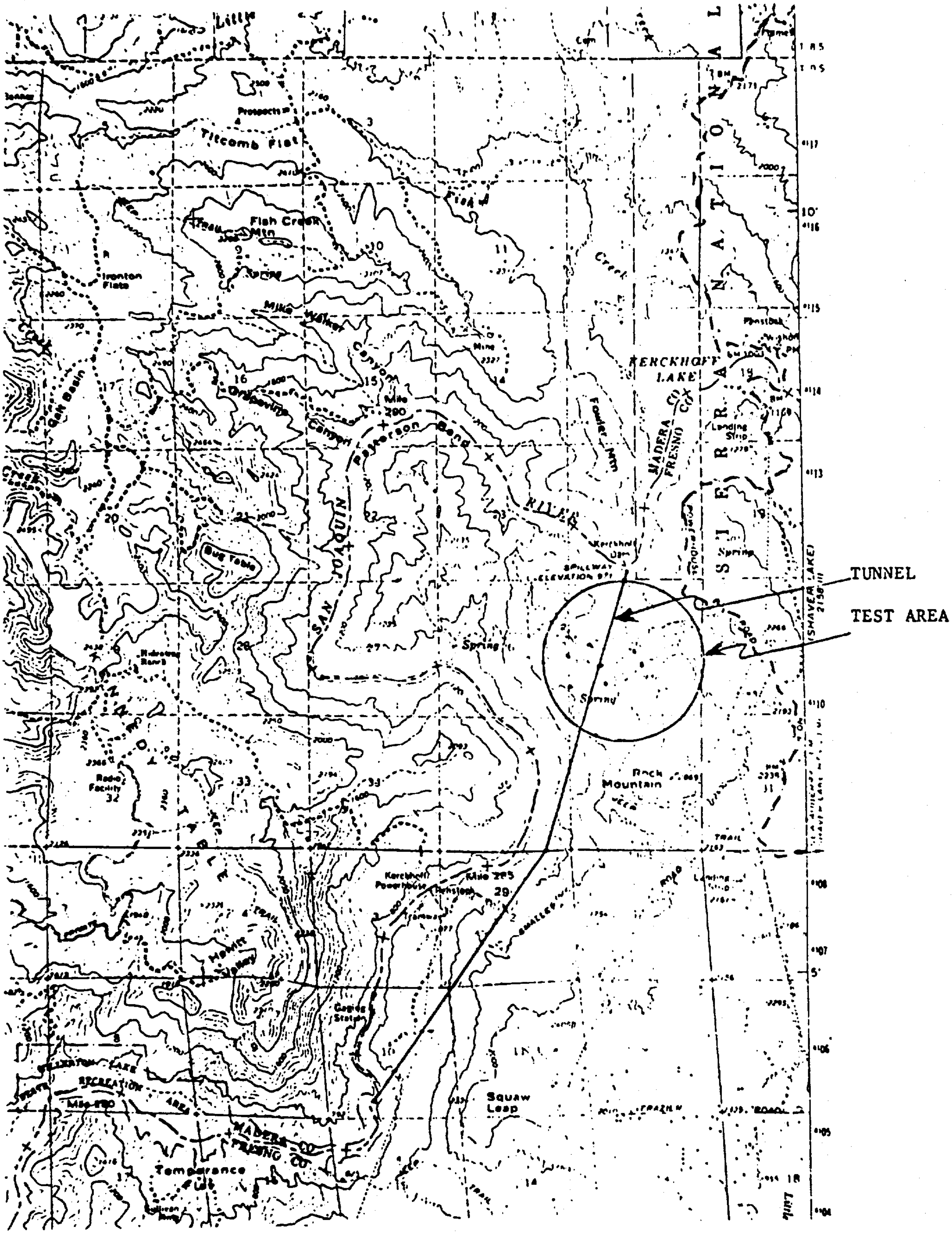

Figure 1. Test area topographical map

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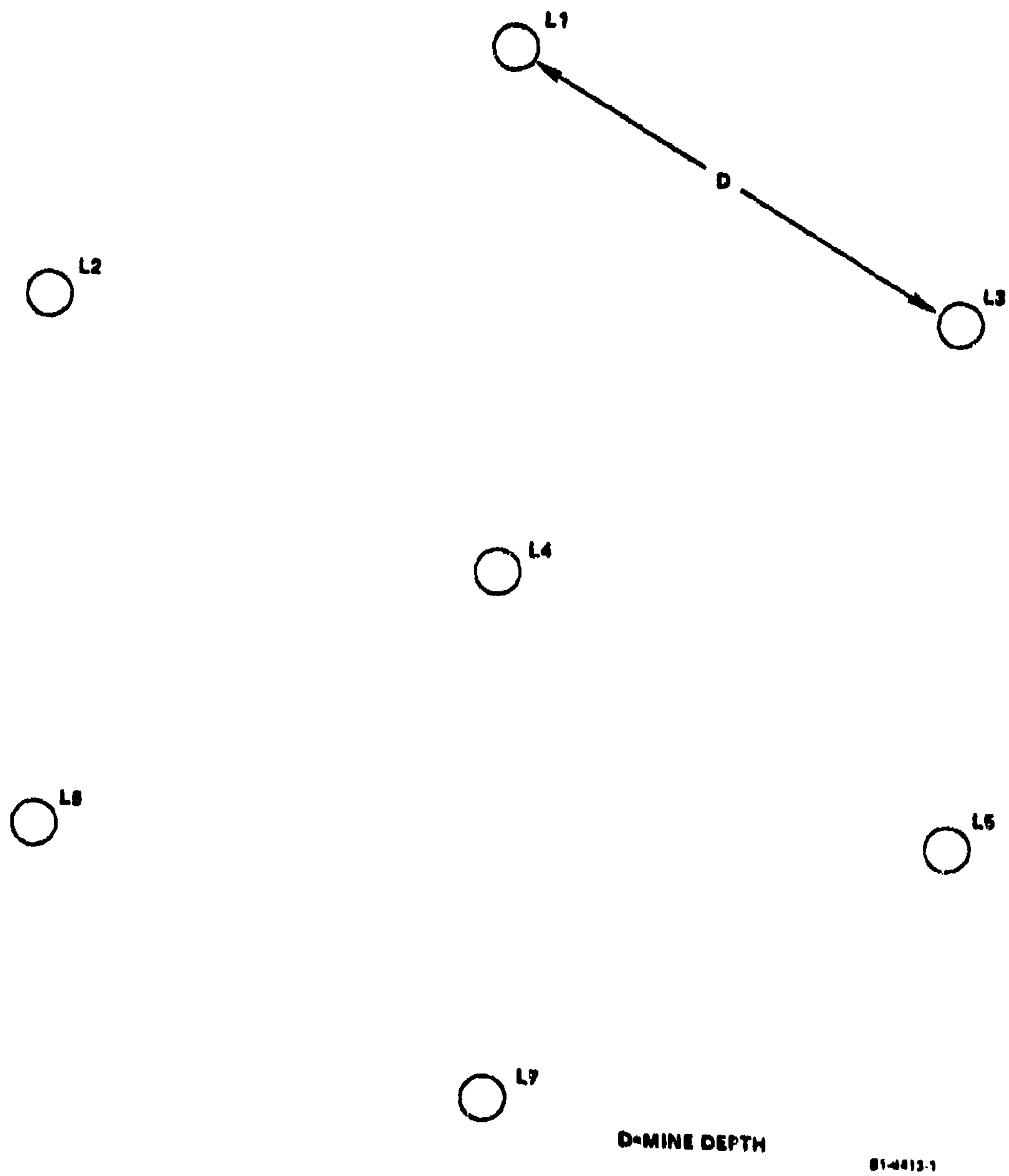
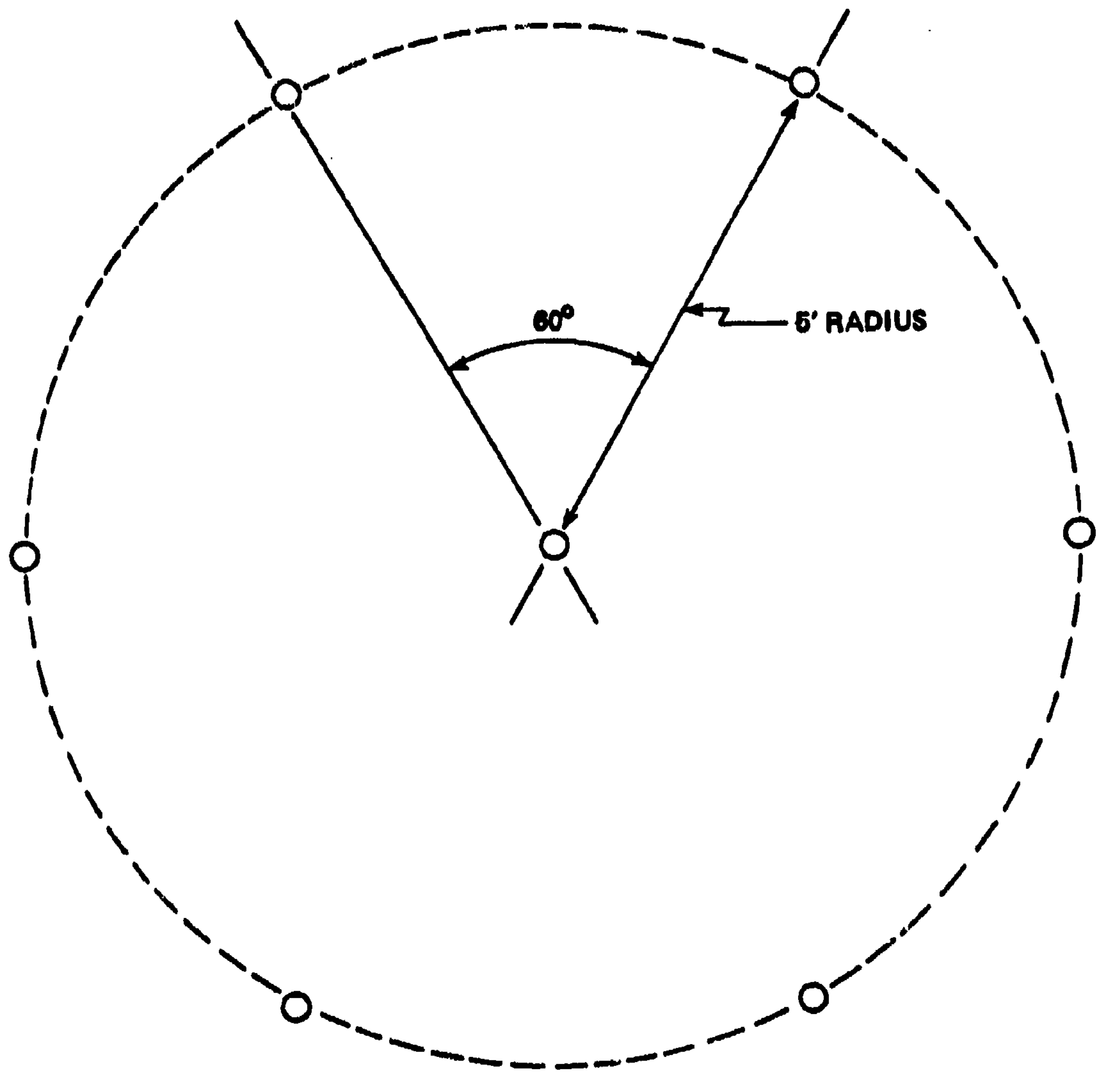
TYPICAL ARRAY



7 PHONE ARRAY



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2.2 SURFACE CONDITIONS

The field test was conducted in the foothills of the Sierra Nevada Mountains. The general terrain was very rugged, with many large rock outcroppings, brush and grass, and scattered large trees.

The geophone subarrays were located on the top of a ridge approximately a mile south of the Kerckhoff Dam. The seismic system vehicles were set up in the tramway parking lot, directly above the dam.

Individual subarray location conditions were all virtually the same as described above.

There were no power lines or other sources of interference. However, the fire fighting equipment (bulldozers, planes, helicopters) caused a great deal of difficulty on the first two days of testing.

2.3 UNDERGROUND CONDITIONS

MEO personnel entered the tunnel on 2 occasions for the purpose of performing some pounding tests with the large timber.

The tunnel was reported to be very damp, with a stream of water running between the rails of the track.

Ear protection was required even when the tunnel boring machine was inactive, due to fan noise and other machinery in the face area.

2.4 REFRACTION SURVEY

Two 550-foot refraction surveys were conducted but were inconclusive due to a large spike which triggered all 12 amplifiers at the same time. This made it impossible to distinguish the individual time breaks on each channel. The origin of the spike, which occurred on all 4 shots, is unknown and is being investigated at this time.

However, sufficient information was gathered by running the seismic system's oscillograph at the time of the shots and running the "Big Bang" refraction survey program, to obtain a rock velocity of the order of 17,000 ft/sec.

2.5 SEISMIC TEST RESULTS

The primary purpose of this field test was to demonstrate the ability of the Seismic Location System to detect and locate tunneling activity, whether by manual means or by machine.

Several attempts were made to simulate manual digging by having MEO personnel enter the tunnel and pound on the tunnel walls during the time the tunnel boring machine was down for maintenance. However, due to the seismic noise levels being created in the geophone area by fire fighting equipment, it was impossible to see the blows above the noise on the visicorder.

It was determined this problem would not be detrimental to the overall field test as the Corps of Engineers had already seen the equipment used in that capacity during a previous field test.

Detection of the tunnel boring machine proved to be simple, with the signal level increasing by approximately 10 to 1 when the machine was operating.

The existing system software depends on abrupt changes in signal to noise level (sharp blows) to perform its location routines. The noise generated by the tunnel boring machine was more constant in nature and very few distinct peaks were distinguishable. By processing one of these peak events, a successful location was performed.

Further research into different location techniques is being conducted by Dr. Roy Greenfield of Penn State University. The seismic data obtained during this operation was retained for study and analysis by Dr. Greenfield. Questions pertaining to the seismic results should be directed to him.

3.0 OPERATIONAL PERFORMANCE

3.1 SYSTEM HARDWARE

Some intermittent problems occurred with the preamps, which may have been attributable to the intense heat in the test area (100^{o}+). A method of shading the preamps is being investigated for future field tests in hot climates.

3.2 SOFTWARE

No problems were encountered with any of the software.

4.0 COMMENTS

The general objective of detecting and locating the tunnel boring machine, and determining approximate maximum ranges, were met.

It is believed that sufficient information was obtained during this test series to lead to a reasonable evaluation concerning the potential for applying the seismic technology as practiced by MEO, to the problems of detecting tunnel digging efforts.

It is anticipated that Dr. Greenfield's detailed technical analysis and report of seismic results of this test series will provide a basis for determining whether to pursue this line of seismic investigation; and if so, what sort of tests and equipment modification to plan.